# ADDIS ABABA UNIVERSITY

## ADDIS ABABA INSTITUTE OF TECHNOLOGY

## School of Graduate Studies

## Energy Center

**Master Thesis**

***Modeling and Simulation of a Micro Hydro-Wind Hybrid Power Generation System for Rural Area of Ethiopia***

***(Study Area Hamsa Gasha Village)***

A thesis Submitted to the Addis Ababa Institute of Technology, School of Graduate Studies, Addis Ababa University In partial Fulfillment of the Requirement for the Degree of Master of Science in Energy Technology

By: Berihu Gebreyohannes

Advisor: Dr. Ing. Edessa Dribsa

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APPROVED BY BOARD OF EXAMINERS

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| --- | --- | --- |
| Chairman, Department of Graduate Committee | Signature | Date |
| Dr. Ing. Edessa Dribsa | ______________ | ______________ |
| Advisor | Signature | Date |
| Dr. Ing. Abebayehu Assefa | __________ | ____________ |
| Internal examiner | Signature | Date |
| Dr. Ing. Tesfaye Dama | ____________ | ______________ |
| External examiner | Signature | Date |

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## Abstract

Ethiopia is a developing country, where majority of the population lives in rural areas without access to electricity. And 83% of the total population of country use traditional biomass energy as a basic source of energy. In contrast, the country is endowed with sufficient renewable energy resources which can be used as a standalone electric energy supply system for electrifying remote areas of the country. These resources are mainly micro hydropower and wind which can be used individually or the best combination of one another. The application of hybrid renewable energy system has become an important alternative solution for rural electrification program.

The aim of the work is to model and study the feasibility of micro hydro-wind hybrid system for electrification of a rural area in Ethiopia. Since hybrid combination of renewable energy technologies is generally considered to be the best suited alternative to an expensive grid extension for remote rural areas, this thesis focuses on creating a model for electricity generation from the above mentioned hybrid system for a village which is called Hamsa Gasha found in Oromia regional state. The village is located at Latitude 7°47' N and Longitude 39°03'E. The total population of the village is 3,102 out of which 1,604 are males and 1,498 are females. The village has 586 households, one primary school, two churches, one Mosque, and one health center.

Firstly, the wind energy and hydro power potential of the village is evaluated based on the available primary and secondary data. And the electrical load of the community is estimated taking critical assumptions. Next the energy equipments are selected and modeled based on the electrical load of the village. A standalone wind/micro hydro/battery hybrid system and only micro hydro system options are considered separately in order to electrify the selected village. HOMER simulation software has been used as the modeling and designing tool. For the first option many feasible hybrid system combinations are listed and sorted according to their net present cost. Accordingly, levelized (COE) and breakeven grid extension distance depend on the selected sensitivity variables. The COE the most favorable wind/micro hydro hybrid system is $0.112 /kWh. Likewise, the breakeven grid extension distance of the hybrid system 23.2km.On the other hand the levelized COE of the micro hydro system is $0.035/kWh which is smaller than that of hybrid system. And it is believed that the standalone micro hydro system is economically feasible and pollution frees to implement for this particular.

Key words: - *HOMER, COE, Hybrid, Micro Hydropower, Wind, Electrical Load*

# Contents

## List of Figures

## List of Tables

## List of Nomenclature

| | |
|---|---|
| $A_T$ | Wind turbine rotor area |
| c | Scale factor. |
| $C_{cap}$ | Capital cost of grid extension [$/km], |
| $C_{NPC}$ | Total net present cost of the stand-alone power system [$] |
| $C_{om}$ | O&M cost of grid extension [$/yr/km] |
| $C_{power}$ | Cost of power from the grid [$/kWh], |
| CRF | Capital recovery factor |
| d | Rotor diameter of wind turbine |
| D | Runner diameter of cross flow turbine (m) |
| $E_D$ | Wind energy density |
| f | Frequency |
| g | Gravitational acceleration |
| $H_g$ | Gross head (m) |
| $H_{net}$ | Net head (m) |
| K | Weibull shape factor |
| L | Runner length of cross flow turbine (m) |
| $L_{tot}$ | Total primary and deferrable load [kWh/yr] |
| N | Rotational speed of the turbine (rpm) |
| $N_B$ | Number of blades |
| $n_s$ | Specific speed of turbine |
| $N_s$ | Synchronous speed of generator |
| $P_{atm}$ | Atmospheric air pressure (Pa) |
| $P_m$ | Extracted mechanical power of the rotor |
| $P_{pole}$ | Number of poles pairs. |
| $P_t$ | Theoretical wind power |
| $Q_{des}$ | Stream flow rate |
| R | Specific gas constant (287kJ/kg k) |
| $R_{proj}$ | Project lifetime |
| S | Blade spacing |
| $S_{grid}$ | Breakeven grid extension distance |
| T | Atmospheric air temperature |

| | |
|---|---|
| $t_J$ | Jet thickness |
| $V$ | Upstream wind velocity at the entrance of the rotor blades |
| $V_{av}$ | Average wind velocity |
| $V_d$ | Wind speed at desired height |
| $V_o$ | Downstream wind velocity at the exit of the rotor blades |
| $v_{ref}$ | Wind speed at anemometer height $z_{ref}$ |
| $z$ | Desired height |
| $z_0$ | Surface roughness length |
| $z_{ref}$ | Anemometer height |
| $\eta$ | System efficiency |
| $\eta_g$ | Generator efficiency |
| $\eta_t$ | Turbine efficiency |
| $\rho$ | Air density ($kg/m^3$) |
| $\rho_b$ | Radius of blade curvature |
| $\rho$ | Water density |
| $\Gamma_n$ | Gamma function |

## List of Abbreviations

| | |
|---|---|
| EEPCO | Ethiopia electric power corporation |
| MoWE | Ministry of Water and Energy |
| HCIE | Hydro China International Engineering Company |
| SPV | Solar Photovoltaic |
| PV | Photovoltaic |
| COE | Cost of generating energy |
| CFL | Compact fluorescent lamp |
| PVC | PolyVinyl Chloride |
| FRE | Fiber Reinforced Epoxy |
| VAWT | Vertical Axis Wind Turbine |
| HAWT | Horizontal Axis Wind Turbines |
| GPS | Global positioning system |
| RES | Renewable energy system |
| HOMER | Hybrid Optimization Model for Electric Renewables |
| NREL | National Renewable Energy Laboratory |
| NPC | Net present cost |
| CRF | Capital recovery factor |
| COE | Cost of energy |

# Chapter One

## 1 Introduction

### 1.1 Background

Energy is a fundamental thing for society and economic growth of any country. Today life is very difficult without electric energy because it is one of the driving forces in a growing economy that means electricity runs everything in our everyday life, for instance lights, appliances, and cooling and heating for homes and businesses. However, it is a well known fact that in many developing countries a major proportion of the population lives without electrical power [32]. Ethiopia is a developing country, where majority of the population lives in rural areas without access to electricity [19].

The rapid depletion of fossil-fuel resources and their environmental polluting effect create concern on searching for alternative energy sources. Hybrid renewable energy system has been considered as promising towards meeting the continually increasing demand for energy [1]. Most of the renewable energy resources are free, inexhaustible and the conversion processes are pollution free. The application of hybrid renewable energy system has become an important alternative as power provider in rural electrification program. For isolated systems such as rural electrification, the hybrid energy system has been considered as attractive and preferred alternative sources.

Ethiopia is endowed with sufficient renewable energy resources which can be used as standalone electric energy supply systems for electrifying remote areas of the country. These resources are mainly small scale Hydropower, wind and solar which can be used individually or the best combination of one another. However, traditional biomass energy is the dominant sources of energy in the rural area for about 83% of the total population of Ethiopia [19]. The current electricity supply produced by the centralized energy production authority, which includes large hydroelectric power plants and diesel, is insufficient to meet the economic needs of the rural and urban population. Even if the country has been made improvement of the energy sector, it is difficult to supply all remote areas access to this modern energy without small energy production systems. As a result, the aim of this thesis work is to model and simulate the potentials and viability of a standalone Wind-Micro hydro hybrid system of a village called Hamsa Gasha.

## 1.2 Problem Statement

Even though Ethiopia is rich in renewable energy resources, majority of the population which live in rural areas depend on biomass energy for cooking food and lighting [35]. Due to many reasons most of the villages of the country are not getting electrical energy currently. To connect the rural areas to the grid, high costs and adequate power for the whole country is required. On the other hand there are many bottle neck challenges related with using the traditional biomass energy, such as, the continued depletion of forest resources for firewood has resulted in environmental problems, increasing scarcity and cost of household fuels, particularly firewood increased stress on women and children who usually are supposed to collect fuel, and the cost of petroleum imports has brought worsening impact on Ethiopia's trade balance and foreign exchange availability

Village electrification is a crucial step for improving the socio-economic conditions of rural areas and overall development of the country. A number of benefits can be achieved in accessibility of electricity. Presence of electricity can help to reduce poverty since it creates job employment opportunities for the villagers and promotes a better standard of life and helps economic development by fulfilling the education, health, water supply for drinking and irrigation needs of the rural population. [46]

As a result, the government of Ethiopia is trying to electrify some rural areas by expending much money to extend the existing national grid even though most of the rural areas are potentially rich in renewable energy resources. Extension of the central electricity grid to such areas is either financially not viable or practically not feasible as these locations are geographically isolated, sparsely populated and have a very low power demand [24], and even the insufficient EEPCO's power supply. Renewable energy resources can be used as a stand-alone with minimum cost as compared with the cost required to extend the grid.

Hybrid systems are the most broadly used and cost effective energy sources for rural electrification [33]. Hence supplying energy to the local community from hybrid system will help them improve their life style as well as reduce deforestation. In addition, it will contribute a lot to the achievement of agricultural lead industrialization [46].

## 1.3 Objectives of the research

### 1.3.1 General objectives

The general objective of this research is modeling and feasibility study of Micro Hydro-Wind Hybrid System for electrification of Hamsa Gasha village in Assela district which is in the vicinity of Ketar River.

### 1.3.2 Specific objectives

The general objective of the thesis is achieved by meeting the following specific objectives.

- ✓ Estimation of the wind and micro hydro power potentials of the selected site.
- ✓ Determination of the power and energy demand of the village living in the selected areas, by considering the basic needs of the people.
- ✓ Selection of an optimized hybrid model for providing electricity to the community by considering its overall installation cost and energy cost per kWh.
- ✓ Selection of an appropriate type of hydraulic turbine, wind turbines and batteries depending on the energy demand for the individual sites.
- ✓ Comparison of the investment cost of the hybrid system against the cost required to electrify the areas by extending the national grid.
- ✓ Optimization and sensitivity analysis of the hydro-wind hybrid system.
- ✓ Make conclusion on to reliable power supply using micro hydro/wind power/battery hybrid technology to replace the existing biomass energy.

## 1.4 Overview of Modern Energy Production in Ethiopia

Ethiopia is endowed with huge energy resource potential. In the long run, the resources could enhance the process of rural electrification in the country if harnessed. The total exploitable renewable energy that can be derived annually from primary solar radiation, wind, forest biomass, hydropower, animal waste, crop residue and human waste is about 1,959x103 TCal per year [9].

### 1.4.1 Ethiopia's Energy Institutions Responsibility and Strategy

Concerning the country's energy sector development and expansion the Ministry of Water and Energy (MoWE) is the responsible governmental organ. The organization is also responsible for energy policy drafting, implementation follow up and supervision. Conducting research and studies including development and promotion of rural energy efficient technologies such as improved stoves, solar and biogases is the responsibility of Ministry of Water and Energy. In addition it also has the responsibility to set standards for biofuel and petroleum oil products, depots and retail facilities [19].

There are three supervised institutions under MoWE, which are directly related to the energy sector. These are Ethiopian Energy Agency which is involved in the regulation of the operations in the electricity supply sector including licensing and ensuring safety and quality standards, National Strategic Petroleum Reserve Administration that controls and govern strategic fuel reserve depots located throughout the country to guarantee sustained supply and Ethiopian Electric Power Corporation (EEPCO) [19].

EEPCO is the sole company involved in generation, transmission, distribution and sales of electricity in Ethiopia. The energy generated was mostly delivered to the urban areas of the country through the interconnected network. But few years back EEPCO has started to electrify some selected rural areas of the country [19].

Today, the demand for electricity of the country is constantly increasing due to rapidly growing economies and expansion in industrial sector, and this resulted in shortage of supply in the last few years. This study shows the need to utilize the potential energy resources of the country and to look for other options to electrify the remote rural areas in order to minimize scarcity of supply and to have improved energy supply options.

EEPCO has a short and long term plan to increase the existing generation capacity to block the existing gap. The 2000MW generation capacity will be increased to 10000MW in the coming five-six years [62]. This is mainly achieved by constructing new hydropower plants including the large Renaissance dam with a capacity of 5250MW [63]. But still this will not be easily accessible to most rural areas of the country which are scattered and far away from the national grid since extending the existing grid is not economical as compared to the separated generation power plants.

### 1.4.2 Wind and Hydro Energy Resources Potential of Ethiopia

#### 1.4.2.1 Wind Energy Resource

According to a preliminary study recently completed by Hydro China International Engineering Company (HCIE), Ethiopia’s wind energy resource amounts to over 1,300GW [65].The country is divided in to two regions by the Great Rift Valley and has a diverse landscape coving mountains and plateaus in its highlands and deserts and steppes in its lowlands. The large differences in altitude provide a good wind resource potential. In the Ethiopian highland plateaus wind speed become maximum during the dry season. Whereas, in the low land, such as Ogaden and the eastern parts of the country, average wind velocity reaches maximum values between May and August, that is the rainy season in most of the country [25].

EEPCo has a short and long term plans to mix the country’s the dominant hydro power electrical energy production with other renewable energy sources, such as wind energy, solar energy and geothermal energy. Towards this, two wind park projects are under construction; these are Ashegoda Wind Park (near Mekele) with installed capacity of 120MW and the second one is Adama Wind Park which is divided in to two phases. Currently Adama phase one has been commissioned.

#### 1.4.2.2 Hydropower Potential

Ethiopia is gifted with vast riches of water resources such as rivers, lakes and ground water. It is called as the water tower of eastern Africa because of the 12 major river basins of the many rivers flowing in and out of the country. Economically exploitable hydropower potential was estimated between the ranges of 15,000 and 30,000 MW [25]. Currently large hydro power makes up 95% of Ethiopia's power production with installed capacity of about 2000 MW. In addition the government is constructing large hydro powers including Gelgel GibeIII and the greatest Ethiopian renaissance dam to end energy shortages and to eventually become an energy exporter.

The huge exploitable hydro power potential in the country indicates that also suitable for small scale power generation including Pico, Micro and Mini hydropower. There are hundreds of identified projects for small scale that could be used for the areas which are remote to the grid but close to consumers [25].

## 1.5 Outline of the thesis

This thesis paper includes six chapters. The first chapter is the introduction part that discusses about the background, statement of the problem, objectives of the study, an Overview of modern energy production in Ethiopia that includes hydro and wind energy potential and outline of the thesis.

Chapter two is a literature review part in which different literatures are reviewed related to the study. The basic background theory related to hydropower and wind energy systems are briefly discussed in this chapter. Moreover the different types of hydraulic turbines and wind turbines and their general working principles are also presented in this chapter.

Chapter three tells about the renewable energy resources evaluation, energy demand estimation and description of the village. Data collection technique, wind energy and micro hydro potential of the site also discussed in this chapter.

Chapters four is entitled with modeling of micro hydro-wind hybrid system for the village. It talks about introduction of the software (HOMER), hybrid system modeling and determination of the right type and sizes of components used in each system are covered in chapter three.

Chapter five is all about the results and discussion of the results obtained based on the input of Chapter three. The simulation results, optimization and sensitivity analysis of the hybrid system is discussed. Besides the Comparison of the Grid extension with standalone off grid system is carried out under this chapter.

Chapter six is about Conclusion and Recommendation of the study that presents conclusions that have been derived from this research, followed by recommendations for further study and for practical implementation of a proposed hybrid system.

# Chapter Two

## 2 Literature Review

### 2.1 Related Works

Many studies have been conducted on standalone off-grid electricity generation in Ethiopia and other developing countries. Different method and approaches have been used to evaluate the various renewable energy resources, such as small hydro power, wind turbine, Solar Photovoltaic (SPV), fuel cells and different hybrids of them. And a numbers of research results for a variety of applications have been published. Some of the researches papers are reviewed in the following paragraphs.

Leake E. Weldemariam conducted a research entitled ”Genset-Solar-Wind Hybrid Power System of Off-Grid Power Station for Rural Applications” his study aimed to achieve an efficient and cost competitive system configuration hybrid power sources that could improve the life of people especially in rural areas where electricity from the main grid has not reached yet. The hybrid system consists of diesel Genset, PV-arrays and wind turbines with energy storing devices and power electronic devices has been discussed in this paper. He suggested that renewable energy sources and/or the hybrid sources are cost competitive over the system lifetime even though the huge capital investment of the renewable sources [33].

A study was conducted by Gelma Boneya on Design of PV-Wind Hybrid Power Generation System for Ethiopian Remote Area. His target was to electrify a community of 100 households equipped with a health center and school. He discussed that the life of people in the rural areas where electricity from the main grid has not reached yet can be improved by implementing cost effective PV-Wind Hybrid system. Using HOMER software he obtained results that vary depending on levels of renewable resources penetration. The Cost of energy of the hybrid set up system feasible in his study range from 30 to 40 cents per kilo watt hour. He explained this value is high compared to the current global electricity tariff and the tariff in the country. However, considering the shortage of electricity in the country and absence of electricity usage in rural areas, this cost should not be taken as a decisive factor [21].

Clint developed Hybrid Energy System for Off – Grid Rural Electrification in Kenya, that aims to design a hybrid energy system comprised of wind turbines, diesel generators and batteries to provide electricity for an off - grid rural community of 500 households, one school, one medical center and an irrigation system. He used HOMER software tool to simulate the hybrid system and analyze the results. At 40m hub height and 1.2 USD per liter of diesel, excess electricity was generated in the optimal simulations that indicate connecting such energy systems to national electricity grid is economically viable [14].

Bizuayehu developed hybrid PV/wind/battery power system to replace the existing Diesel power electricity for Kebri Dehar and Degehabur towns of Ethiopia. Both towns are remotely located from the national grid. He identified two power supply options; hybrid (standalone solar/wind/battery) system and extending new transmission line from nearest substation of the national grid to the selected towns. And he designed for both options using the HOMER simulation program as a design tool. The simulation results of hybrid system composed of solar/wind/battery indicated that the best option with the cost of generating energy (COE, US$/kWh) found 0.422 $/kWh and 0.441$/kWh for Kebri Dehar and Degehabur towns respectively. Whereas the simulation result for the grid extension of energy cost are 1.172 and 0.869 $/kWh for Kebri Dehar and Degehabur towns respectively. According to the software result the grid connected option was found to be not economical feasible solution comparing with hybrid system to supply power for the two towns [10].

Getachew Bekele conducted a research for his doctorial dissertation on solar-wind hybrid energy resources. The aim of the study was to examine supplying electric energy from solar-wind hybrid resources to the poor population residing in the countryside and people relocated by the Government from the over used and dry regions to relatively productive and fertile areas to reduce poverty. For community of 200 families with five to six family members in each a hybrid standalone supply system was intended to provide electricity. And the community electric loads are used for lighting, water pumping, a radio receiver, and some clinical equipment for health center. The analysis is done With HOMER. Numerous alternative feasible hybrid set-ups with different levels of contribution results were achieved and the costs of the feasible set-ups obtained in this study are high, in the range of 30 to 40 cents per kilowatt hour. He suggested that the energy cost of the hybrid system is high however considering the shortage of power in the country and protection of vegetation and forestry the cost is preferable [22].

Most the previous authors concentrated on electrifying rural areas using PV-Wind hybrid in general. Therefore, enough research work is not available on Micro Hydro-wind hybrid system. In addition, most studies concentrate on supplying electricity simply for domestic purposes and do not take into account the electricity demand for agricultural irrigation and community purposes .Unlike the previous studies, the main focus of this thesis work is to model and simulate a micro hydro – wind energy hybrid system using HOMER as optimization and simulation tool for specific location called Hamsa Gasha.

## 2.2 Micro Hydro Power Generation System

### 2.2.1 Introduction

Hydroelectric power is one of the most commonly used among the various renewable energy resources. The potential energy of water at the higher altitude discharges to drive turbine or water wheel. Turbines are used to convert kinetic energy of moving water into torque energy. The turbine and generator spins together when the moving water strikes the blade of turbine since the turbine and generator are connected together with a shaft. The mechanical energy of the turbine is transferred into electrical energy of the generator via the shaft [37]. Hydropower has certain advantages comparing with the other energy resources, such as

- Water is naturally available resource
- There is minimum or no pollution during operation
- Hydropower reduces green house gas emissions

### 2.2.2 Type of hydropower plant

Even though there is no common standard classification of hydropower, can be classified in to two major groups based on the construction and size of the plant.

#### 2.2.2.1 Classification of Hydropower based on construction

Based on the construction of hydropower there are three types of design .These are impoundment diversion run of river and pumped storage.

**Impoundment**

Typical large hydropower plants heads the construction of dams used to store more volume of water to provide sufficient head behind the dam. The stored water in the reservoir is required to get large amount of output power by improving the head and constant flow the through the turbine .In addition the reservoir is used to store water for dry season [16].

### Run-of-River

The power output of run-of-river small hydro plants fluctuates with the hydrologic cycle, so they are often best suited to provide energy to a larger electricity system. Run-of-river type of power plant in which, the hydro plant uses only the water that is available in the natural flow of the river. The water is diverted from the natural stream flow into canal penstock. Run of the River plants do not need dam or store water. The facilities depend on the discharge curve of the river and the turbine generates electricity as water is available. The power output of run-of-river small hydro plants fluctuates with the hydrologic cycle .Therefore this types of power plants are viable only ,if the minim dry season flow is enough to generate the demand load of at all times .Typical run-of- river plant consists of either a low level diversion weir or a stream bed intake .The advantage of these structures is used to provide constant flow of water into the turbine .The weir or bed intake directs the water to the power house through the penstock [51]

**Pumped storage**

Pumped storage is a dual action water flow system. During off peak hours water is pumped up to the higher reservoir from the lower one using reversible pumping turbine .The stored potential energy of water is released back to the lower reservoir to spine the turbine to generate power during peak hours [12].

#### 2.2.2.2 Classification of Hydropower by Installed Capacity

The classification according to installed capacity is the most frequent form of classification used in hydro power although there is no internationally agreed range. Because of the different development policies in different countries classification of hydropower varies from country to country. The table below gives a general classification ranges accepted by most countries [52].

Table 2-1:- classification of hydropower plants [36]

| S.Nº | Type of hydro plant | Size in KW |
|---|---|---|
| 1 | Pico | <5 |
| **2** | **Micro** | **<100** |
| 3 | Mini | 100-1000 |
| 4 | Small | 1000-10,0000 |
| 5 | Medium | >100,000 |
| 6 | Large | >500,000 |

Since the energy demand of the selected village is not as high as urban areas a micro hydro size and run-of river type is selected for this study. And the minim dry season flow is enough to generate the energy demand of the selected at all times hence run-of- river type is feasible in our case.

### 2.2.3 Types of hydropower turbines

As water falls from the upper position to the lower one through the penstock or tunnel ,its potential energy is converted into electrical energy with a prime mover referred as hydraulic turbine .Hydraulic turbine consists of vanes ,blade ,or buckets due to the action of water pressure and velocity. The rotary action of the turbine in turn spines a shaft that is integrated with an electrical generator that converts the torque energy of the shaft in electrical energy .The rotating part of a hydraulic turbine is called runner [51].

Even though there are many classification of turbines ,they can be broadly classified into two types either impulse or reaction turbine .This classification criteria is based on the impact of the water energy with respect to hydraulic turbine .Impulse turbine converts the kinetic energy jet of water on air into torque energy when the jet hits the turbine runner .On the other hand ,reaction turbine is totally immersed into the water .Reaction turbine develops power from the combined effects of pressure and kinetic energy of the moving water .The angular and linear momentum of the water is transferred into shaft power in reaction turbine [12].

Types of hydraulic turbines are selected for a particular site based on different criteria's, such as head flow rate efficiency and cost [17].

#### 2.2.3.1 Impulse turbine

Water is directed from upper to lower stream through pipe or penstock to drive the turbine. In impulse turbine, before the water reaches to hydraulic turbine, it passes through nozzle which squeezes the flow in to a narrow and high velocity jet of water. Potential energy of the water that passes through the penstock is converted in to kinetic energy jets of water. The jets of water strikes the runner tangentially and discharged to atmospheric pressure .The jet of water, before it hits the blades of the runner is guided through the use of bulb-shaped needle in a nozzle. Impulse turbines are typically used for high head and low stream flow application and they are also categorized in either pelton or cross flow turbines [17].

### Pelton turbine

A pelton turbine has one or more free jets of water discharging in to the atmosphere and strikes the buckets of the runner .The runner carries a large numbers of buckets on its periphery. Pelton turbine has three fundamental components; these are nozzle, a runner and a casing. The buckets are split in to two halves in order to avoid the interference of the return jet with the oncoming one. The jets of water impinging on the buckets of the runner transfer momentum by spinning the turbine. The lower lip of the bucket has a cut way profile. This is used to permit the following bucket to further before cutting off the jet projecting to the bucket ahead of it and also allows a smoother entrance of the bucket into the jet [17].

Figure 2-1 Pelton turbine [55]

### 2.2.4 Cross flow turbine

Across flow turbine is a drum-shaped machine that uses an elongated rectangular selection nozzle directed against curved vanes on a cylindrical shaped runner, it looks like a ‘’squirrel cage’ blower. Cross flow turbines consists of two parts; a nozzle and a turbine runner. Cross flow turbine allows the water to flow through the blade two times .When the water flows from outside of the blade to inside is the first pass. The second pass is when the water passes from inside buck to outside [56].

The advantage of cross flow turbine is they can be easily manufactured, cheap and easy to repair. And they can be operated to generate even during low flow rate period. One disadvantage of cross flow turbine is low efficiency compared to other turbine. Generally cross flow turbine are designed for larger flow of water and lower head than pelton turbine.

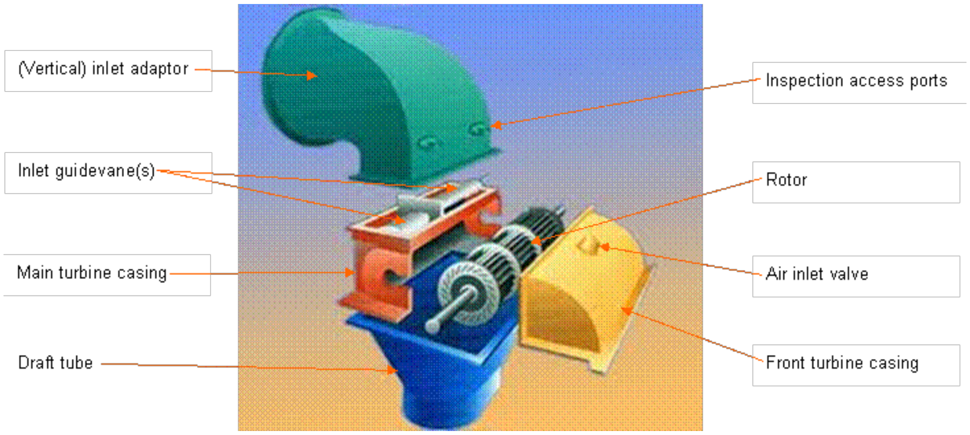


Figure 2-2 Cross flow turbine [56]

#### 2.2.4.1 Reaction Turbine

The direction flow of water with respect to water wheel determines the designs of reaction turbines. If the flow direction is perpendicular to the axis of rotation, the runner is called a radial-flow reaction turbine. If the water flow is somewhat in between radial and axial direction, it is known as a mixed flow reaction turbine. In contrast, if the direction of flow is parallel to the axis of rotation turbine is axial flow turbine. Reaction turbines are generally recommended for sites with lower head and higher flows compared with the impulse turbines [12].

## Francis turbine

The most common mixed-flow turbine is Francis turbine that was developed by James B. Francis turbine consists of fixed runner blades and adjustable guide vanes, used for medium heads. The water enters in to the turbine by the spiral case that is intended to keep its tangential velocity constant along the successive sections and mobile guide vanes control the discharge going into the runner and adjust the inlet angle of the flow to the runner blades angles. The runner blades are profiled in a complex manner and direct the water so that it exits axially from the centre of the runner so that the water transfers most of its pressure energy to the runner before leaving the turbine through a draft tube [12].

Figure 2-3 Francis turbine [58]

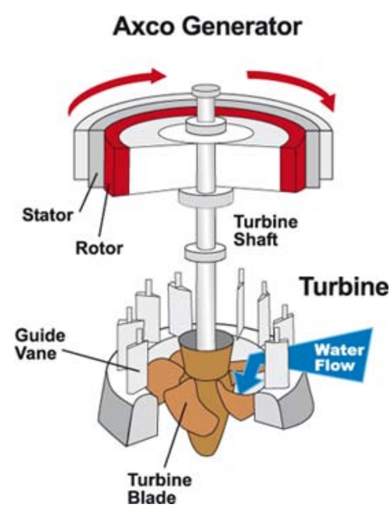


Figure 2-4 Kaplan turbine [59]

**Kaplan and Propeller Turbines**

Both, Kaplan and propeller turbines are axial-flow reaction turbines. The Kaplan turbine is built with coordinated adjustable blades and gates. The automatic coordination of the movement of runner blade and adjustment of the gate position provides optimum –hydraulic performance, So that the turbine can operate over a wide range of flow and low-head application at better efficiencies. Fixed runner blade of Kaplan turbines are called propeller turbines. The runners of Propeller turbines are rigidly attached to the hub. And known as a fixed blade axial flow turbine since the pitch angle of the rotor blades cannot be changed. They are used when both flow and head remain practically constant [12].

### 2.2.4.2 Turbine Selection and Formulas for the Principal Dimension of the Turbine

The type, geometry and dimensions selection of turbine is carried out based on head, discharge Rotational speed, Cavitations and Cost. The net head is the first criteria to take into account in the turbine's selection. Impulse turbines such as Pelton turbines work effectively at high head. Some turbines like the cross-flow and the Kaplan work efficiently with a large range of flow variation while others like the propeller turbines work only for a narrow range of flow variation with their efficiency falling quickly with a little variation in flow. The selection of type of turbine that is desired to run the generator of the hydropower site is supported by tables, charts and graphs taking all the above variables in to consideration [18].

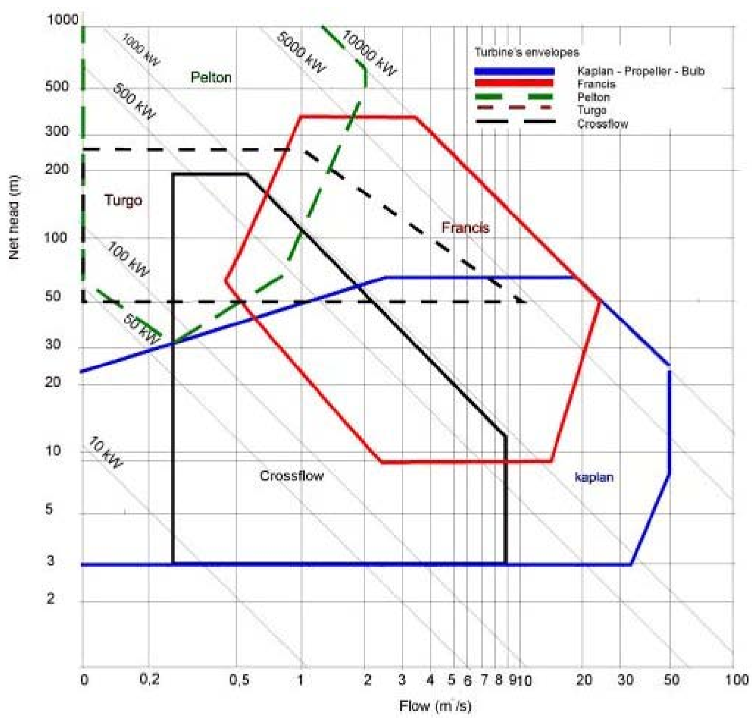


Figure 2-5 Turbine selection chart [60]

Based on turbine selection chart, the available head and design flow rate of the selected micro hydro site lies in the cross flow turbine range. Hence cross flow turbine is selected for this thesis. Cross flow turbine is suitable for run-of-river type micro power plant because it can be operated even during low flow rate period. In addition flow turbines can be easily manufactured in domestic industries to minimize cost and hard currency.

#### 2.2.4.3 Principal Dimension of the Selected Turbine

The electromechanical components of Micro Hydro Power system are the turbine, generator and other equipments such as the control system in the power house. Under this section the principal dimensions of the turbine is carried out, depending up on the proved science and engineering laws as well as international guidelines and practice.

Based on the selection criteria discussed in the literature part, Banki cross flow turbine is selected for this study. The Performance characteristic of this turbine is a constant efficiency with wide range of flow from 30% to 100% of rated discharge and head condition. Cross flow turbines are free from cavitations, the runners are self cleaning, and maintenance is less complex than for other types of turbines. Cross flow turbine can be manufactured in domestic industry with the available local materials. The major dimensions of cross flow turbine are estimated in this sub section.

The main parameters of cross flow turbines are the runner length, runner diameter, number of blades, space between the blades and jet thickness. These parameters can be estimated using the following formulas given that the rotational speed (N) of the turbine in rpm, design flow (Q) for the turbine and the net head with the empirical formulas [11].

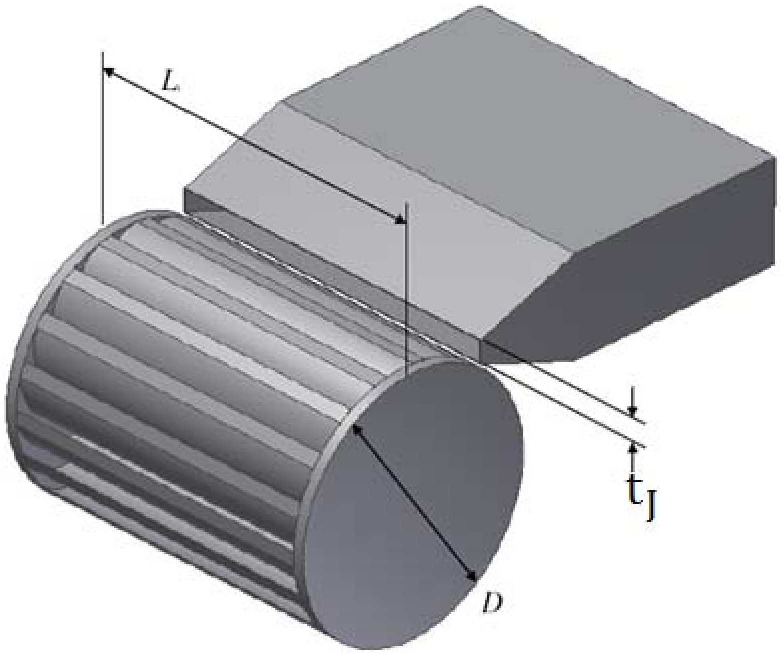


Figure 2-6:- principal dimensions of cross-flow turbine [11]

- **Runner diameter (D)**

According [6] and [11] the runner diameter can be sized using the equation given below.

$$D = \frac{39.819\sqrt{H_{net}}}{N} \qquad (2.2.1)$$

Where,

D is the runner diameter (m), H is the net head (m) and N is speed of turbine in r.p.m

- **Runner length (L)**

The product of runner length (L) and runner diameter (D) gives a constant value [V] as explained in the equation below.

$$L * D = 2.627\frac{Q}{\sqrt{H_{net}}} \qquad (2.2.2)$$

$$L = \frac{2.627Q}{D\sqrt{H_{net}}} \qquad (2.2.3)$$

- **Jet thickness ($t_J$)**

The area of jet can be determined easily. This also enables to calculate the optimum thickness of jet or thickness of the nozzle which is the same thickness of jet.

$$\text{Jet area}(A_J) = \frac{Q}{C\sqrt{2*g*H_{net}}} \qquad (2.2.4)$$

Where C is the smoothness or roughness of the nozzle, typically this constant ranges from 0.95 (rougher nozzle) to 0.99 (smoother nozzle)

$$\text{Jet thickness}(t_J) = \frac{A_J}{L} \quad (2.2.5)$$

The above equation can be simplified as follow

$$t_J = 0.22\frac{Q}{L\sqrt{H_{net}}} \quad (2.2.6)$$

- **Blade space(s)**

Blade spacing is the distance between the tips of two adjacent blades on the outer periphery. This value can be obtained by the formula indicated below [11].

$$s = k\frac{D}{sin\beta} \quad (2.2.7)$$

Where, k is an experimental coefficient which relates the jet thickness to the diameter of the runner. This value ranges from 0.075 to 0.1and $\beta$ =$30^0$ is blade angle [2].

- **Number of blades ($N_B$)**

$$N_B = \pi\frac{D}{t_J} \quad (2.2.8)$$

- **Radial rim width α**

Radial rim width is the difference between the outer and inner radius measured radially and can be sized by the equation below.

$$\alpha = 0.17 * D \quad (2.2.9)$$

- **Radius of blade curvature ($\rho_b$)**

All blades are made from arcs of a circle and radius of blade curvature is found using the equation given below

$$\rho_b = 0.163 * D \quad (2.2.10)$$

### 2.2.5 Civil Work Components of Micro Hydro Power Plant

Civil works structures manage the water that runs through hydropower system. It is important to know that civil structures should be built in appropriate sites and designed for optimum performance and stability. In order to reduce cost and ensure a reliable system, the following factors should be considered, the best use of local materials and local labor, selection of cost-effective and environmentally friendly structures [13]. Some of the main components of hydro powers are listed below.

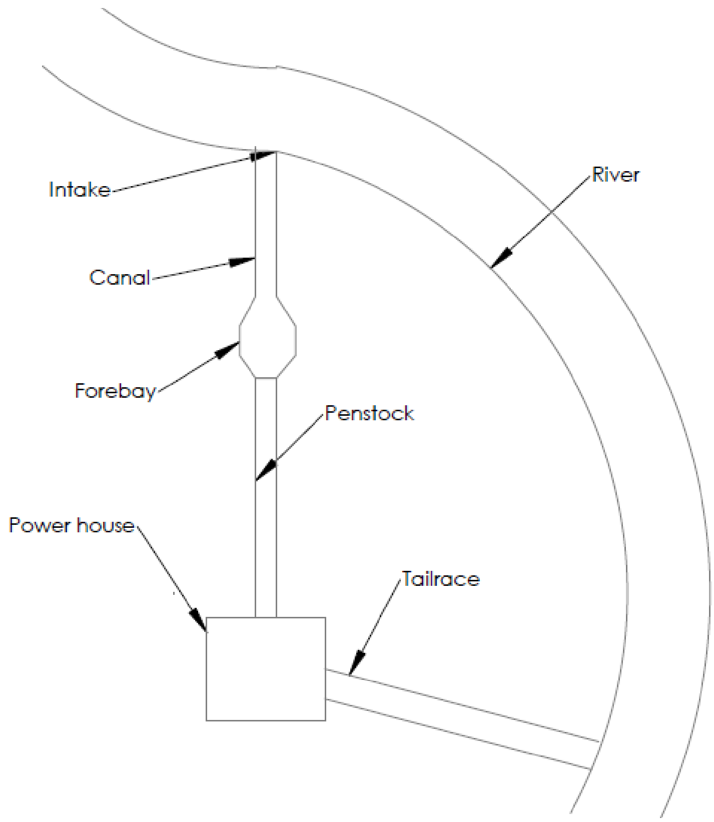


Figure 2-7 Layout of micro hydropower system

#### 2.2.5.1 Canals/Channels

The canal transports the water from the intake to the forebay tank. The canal cross section and alignment should be designed for optimum performance in order to reduce losses due to friction and leakage. When water flows in the channel, it loses energy in the process of sliding past the walls and bed material. Friction loss inside the channel is directly proportional the roughness of the material, and the higher friction loss results to the higher head drop needed between channel entry and exit. Thus most canals and channels are built to minimize friction and avoid leakage; channels are often sealed with cement, clay or polythene sheet. The size and shape of a channel are often a compromise between costs and reduced head [18].

There are three determining variables in canal hydraulics, depth of flow width of flow, and the slope of the canal, fixing two will give the third. The input parameters in determining canal cross sectional dimensions and canal slope are the flow rate, velocity of the water through the canal, canal profile and the roughness coefficient. The required flow rate is the design flow rate for the system, whereas the roughness coefficient is constant that depends on the material from which the canal is made [18].

**2.2.5.2 Penstock**

The penstock is a conduit or a pipe which conveys water under pressure from a canal or reservoir to the turbine located at the power house. Penstock is place where the potential energy of the water is converted into kinetic energy in order to rotate the turbine. Based on the principle of operation, penstock can be classified as either pressure or siphon penstock. The pressure penstock discharges the water to the turbine always under a positive pressure (greater than atmospheric pressure). Whereas the siphon penstock works under lower pressure may be less than atmospheric pressure and sections of the conduit act as a siphon so that it requires a vacuum pump or some other means for initiating the siphon action must be used to fill the conduit with water and to evacuate air in the conduit [41].

Penstock is one of the most expensive components in the hydro power project, so that it is important to optimize its design in order to minimize its cost. The choice of size and type of penstock depends on many factors. Basically, the trade-off is between capital cost and head loss. Head loss due to friction in the penstock pipe depends mainly on the velocity of the water, the roughness of the pipe wall and the length and diameter of the pipe. Head loss due to friction in the pipe decrease dramatically with increasing pipe diameter, conversely, pipe costs increase steeply with diameter. Therefore a compromise between cost and performance is required [13].

In the penstock, the water pressure is built up on the way to turbine. The pressure rating of the penstock is critical because the pipe wall must be thick enough to withstand the maximum water pressure; otherwise there will be a risk of bursting. The pressure of the water in the penstock depends on the head; the higher the head, the higher the pressure [13].

Penstock pipes are characterized by materials type, diameter, wall thickness, type of joint and availability. The material is selected according to the ground conditions, accessibility, weight, jointing system and cost. The most commonly used penstock materials are listed below.

- PVC (PolyVinyl Chloride)
- Steel
- Polyethylene
- FRE (Fiber Reinforced Epoxy)
- Transite (asbestos cement)

A satisfactory penstock diameter depends on three factors, these are energy losses due to friction between the water flowing in the pipe and the inside pipe wall, pressure limitations of the pipe as a function of wall thickness and Cost of the pipe and installation. For a given flow rate, the smaller the pipe diameter is the higher the velocity of the water. Since friction is a function of velocity as velocity increases, friction increases. Conversely, a larger pipe diameter means that slower velocity and consequently minimum friction. However the cost of the pipe increases significantly with the increase in size. The wall thickness is selected to resist the maximum internal hydraulic pressure, including transient surge pressure that will occur [7].

Generally, according to type of construction materials, Penstocks may also be classified as Concrete penstock**,** Fiberglass or plastic pipe, Steel penstock, Wood pipe [12]

#### 2.2.5.3 Settling Basin

The water flow from the river and enter to the turbine typically carry a suspension of small particles. These particles composed of hard abrasive particles such as sand which can cause damage and rapid wear to turbine runner's, penstock materials and valves. Hence the water which is used to spine the turbine should be separated from these solids. The presence of settling basin structure is essential to remove this silt load, the water flow must be slowed in the structure in order for the particles to settle and collect on the basin floor. The function of the settling basin is to settle out the particulate matters floating in the water to the bottom of the components in order to prevent a possible damage of sediments on the hydro mechanical equipment [13]. To ensure that there is enough space for further deposits these deposits needs to be flushed periodically. The building which houses the settling area should be placed at the channel entry or at the penstock entry [13].

#### 2.2.5.4 Power House

Power House is a place in which electromechanical equipments are placed in it and mechanical energy is converted into electrical energy. The power house protects the turbine and the equipment required for the production of electricity from rain and other factors. The main machineries of the power house are the hydraulic turbine, the electrical generator and controller units. Depending on the geographical condition of the selected site, the power house may be built on the surface of earth or underground .The foundation powerhouse must be solid, even though its structure is simple [41].

#### 2.2.5.5 Tailrace

The tailrace is a channel that allows the water to flow back to the stream after it has passed through the turbine. There are two different design of tailrace for impulse and reaction turbine. Impulse turbines can have relatively high outlet velocities, so that the tailrace should be designed to guarantee that the powerhouse is safe. In the case reaction turbine the level of the water in the tailrace influences the operation of the turbine and more specifically the initiate of cavitations. This level also determines the available net head and in low head systems may have a decisive influence on the economic results [41].

#### 2.2.5.6 Surge Tanks

Destruction of the penstock due to the waves generated from sudden valve opening and closing can be protected with the help of surge tanks. Surge tanks are vertical standpipes that act as a forebay and shorten the distance for relief from the pressure wave of water hammer. A surge tank has three purposes in a hydropower plant. It provides flow stabilization to the turbine, it reliefs water hammer or regulates pressure, and it improves speed control. Surge tanks are typically not economical unless most of the drop in elevation in the penstock occurs near the turbine [12].

#### 2.2.5.7 Forebay Tank

The forebay is a pond or basin of enlarged water that links channel and the penstock. The main role is to permit the last particles to settle down before the water enters the penstock. Regarding on its size it can also serve as a reservoir to store water. The water volume of the forebay is made to balance the variations of the water gauge while operating the turbine [37].

#### 2.2.5.8 Intake

The intake is constructed directly at the mouth the river. A weir built across to the flow direction block the water. This structure allows a regulation of the water directed to the canal. In dry phases all the water can then be diverted directly into the canal. However, if there is too much water, the intake of the canal can be throttled. The extra water flows along the weir. Similarly, it is possible to avoid too much water entering the canal to prevent from devastation of the constructions [13].

## 2.3 Wind Resource Assessment

### 2.3.1 Introduction

The natural movement of air across the earth surface is called wind. This natural movement of air results due to uneven heating and cooling of the earth atmosphere and its rotation, wormer air raises upward leaving space and this space is replaced by cooler air and this results local wind. The rotation of the earth and surfaces features such as mountains and valleys can change the speed and direction of wind. The kinetic energy of wind is converted in to electrical energy by a machine called wind turbine [48]. Wind turbine is primary energy converter component .And wind energy is one of the most promising forms of renewable energy.

Generating energy from the wind is not a new idea .Wind turbines have been used for thousands of year for pumping water milling grain, powering sawmills, and other mechanical power applications by ancient people. Wind turbine technology has developed rapidly in recent years specially, in 1970's oil crisis with the rekindling of interest in sustainable and secure power production. Today, there are millions of wind turbines in operation around the world. Most of them are used for water pumping and for generating electricity. Wind power is the fastest growing energy source over the world since wind energy is emission free and non-polluting diverse energy supplies [50].

### 2.3.2 Wind Speed Distribution

The energy available in the wind varies as the cube of wind speed. Because of this the wind speed is the most significant data required to evaluate the power potential of a particular site. Wind is influenced by weather system, local land terrain, and elevation of the site. It is never stable at any site. Wind is highly variable, both in space and in time. Wind speed varies within minute, hour, day, season, and even year. Consequently, an averaged of 10 or more years annual mean speed is required for the selected site. The wind-speed variations over the period can be described by a probability distribution function [39].

### 2.3.3 Weibull Probability distribution

In Weibull distribution, the variations in wind velocity are described by two functions: The probability density function and the cumulative distribution function. A probability density function (f (v)) best states the variation in wind speed. It is used to model the wind velocity variation. A probability density function (f (v)) provides the probability that an event will occur between two end points. The area under the curve between any two speeds greater than zero will equal the probability that wind will blow somewhere between those two speeds.

The probability density function (f (v)) indicates the fraction of time for which the wind is at a given velocity v and is expressed as:

$$f(v)=\frac{k}{c}\left[\frac{v}{c}\right]^{k-1} e^{-(v/c)^k} \qquad (2.3.1)$$

Where, k is the Weibull shape factor and c is scale factor.

For a given average wind speed, a larger shape factor indicates a relatively narrow distribution of wind speeds around the average while a smaller shape factor indicates a relatively wide distribution of wind speeds around the average. The Weibull probably density function is normally known as the Rayleigh density function if k = 2. Then above equation can be simplified as follow.

$$f(V) = \frac{2V}{C^2}\exp\left[-\left(\frac{V}{C}\right)^2\right] \qquad (2.3.2)$$

The cumulative distribution function is F (v) is the integral of the probability density function. The cumulative distribution function of the velocity V shows the fraction of time that the wind velocity is equal or lower than V

$$F(v) = \int_0^{\infty} f(v)\,dv = 1 - e^{-(v/c)^k} \qquad (2.3.3)$$

Under the Weibull distribution, the main factor determining the uniformity of wind is the shape factor k and uniformity of wind at a site increases with the shape factor k [47].

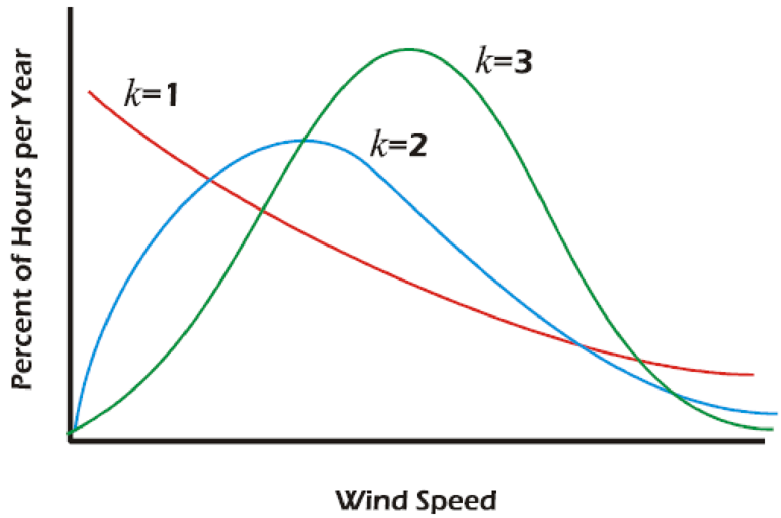


Figure 2-8 Weibull Distribution Shape parameters [30]

### 2.3.3.1 Wind Shear Formula

The wind data available at meteorological stations might have been collected from different anemometer heights. It is very important that the measuring equipment is set high enough to avoid turbulence created by trees, buildings or other obstructions. In most cases the data are recommended to log at 10 m. It is important to adjust the measured wind speed to the hub height for wind energy calculations. This can be done using the logarithmic law, which assumes that the wind speed is proportional to the logarithm of the height above ground. The data collected at any heights can be extrapolated to other heights on the basis of the roughness height of the terrain. Due to the boundary layer effect, wind speed increases with the height in a logarithmic pattern. If the wind data is available at a reference height $z_{ref}$ , then the velocity $V_d$ at a hub height $Z_{ref}$ is given by equation below [47][26].

$$V_d = \frac{V_{ref}\ \ln\left(\frac{Z}{Z_o}\right)}{\ln\left(\frac{Z_{ref}}{Z_o}\right)} \qquad (2.3.4)$$

$V_d$ = wind speed at desired height (z) above ground level

$v_{ref}$ = reference speed, i.e. a wind speed at height $z_{ref}$

z = height above ground level for the desired velocity v

$z_{ref}$ = reference height, i.e. the height at which wind speed is $v_{ref}$,

$z_0$ = surface roughness length in the current wind direction

Table 2-2: - Surface roughness lengths value of different terrain (HOMER)

| Terrain Description | $z_0$ |
|---|---|
| Very smooth, ice or mud | 0.00001 m |
| Calm open sea | 0.0002 m |
| Blown sea | 0.0005 m |
| Snow surface | 0.003 m |
| Lawn grass | 0.008 m |
| Rough pasture | 0.010 m |
| Fallow field | 0.03 m |
| Crops | 0.05 m |
| Few trees | 0.10 m |
| Many trees, few buildings | 0.25 m |
| Forest and woodlands | 0.5 m |
| Suburbs | 1.5 m |
| City center, tall buildings | 3.0 m |

### 2.3.4 Air Density

Air density varies with the variation linearly with the atmospheric pressure, temperature and elevation. The higher the altitude the less dense the air, thus the air density is the function of pressure and temperature and explained by the gas law as follows [39].

$$\rho = \frac{P_{atm}}{RT} \qquad 2.3.5$$

Where $P_{atm}$ is atmospheric air pressure (Pa) R is the specific gas constant (287JK/kg) and T is air temperature in k

Knowing the temperature and elevation of a particular site it is possible to calculate air density using the following relation [47]

$$\rho = \frac{353.049}{T} e^{-0.034\frac{Z}{T})} \qquad (2.3.6)$$

### 2.3.5 Swept area

The power output of wind turbine is also depend on the rotor swept area of the turbine .The swept area of HAWT is determined as follow.

$$A = \frac{\pi d^2}{4} \tag{2.3.7}$$

Where d is the rotor diameter

Larger blade length or rotor diameter result larger swept area and wind turbine with larger swept area generate more electrical energy.

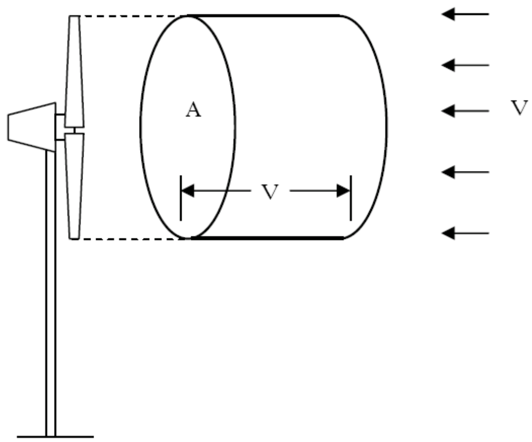


Figure 2-9 Wind rotor swept area [47]

### 2.3.6 Wind Energy Conversion Systems

Wind turbines are machines that convert the kinetic energy of the wind into mechanical energy. If the mechanical energy is directly used for pumping water or grinding stones, the machine is called a windmill. If the mechanical energy is converted to electricity, the machine is called a wind generator. There are different designs of wind turbines. Most of them consist of a rotor that turns round propelled by lift or drag forces, due to the interaction the blades with the wind. Depending on the position of the rotor axis, wind turbines are classified as either vertical-axis or horizontal axis [34].

#### 2.3.6.1 Vertical Axis Wind Turbine (VAWT)

The axis rotation of VAWT is perpendicular to the ground and wind direction. Yaw mechanism is not necessary for VAWTs, since they receive wind from any direction .The generator and gear box of VAWTs are sated at the ground level, so that the design of the tower is so simple, economical and easy to maintain [34].

The negative aspect of VAWT is, they are not self starting machines, and additional mechanisms is required to start the turbine when it is stopped or when the wind direction is changed .VAWT can be classified in to two categories depending on the type of force. Savonius type of VAWTs use the drag force where as durries types of VAWTs use left forces [34].

#### 2.3.6.2 Horizontal Axis Wind Turbines (HAWT)

The axis of rotation of horizontal axis wind turbines is parallel to the horizontal ground and to the direction of wind stream. Generally Horizontal axis wind turbines have blades starting from one up to many .A wind turbine is called single blade, if the wind turbine has one blade only. A wind turbine with two number of blade is called double blade wind turbine. Three bladed wind turbines is called triple blade wind turbine. If the wind turbine has more than three blades, it is known as multiple blade wind turbine [44].

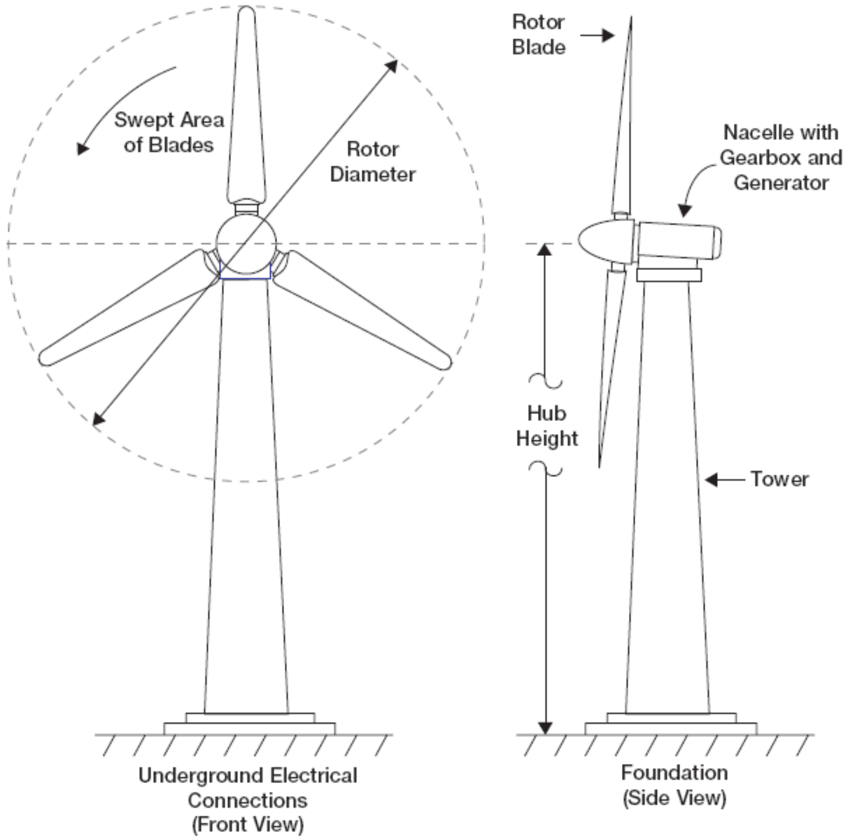


Figure 2-10 Three bladed HAWT [44]

Depending on the face of blades of wind turbine with respect to the wind direction, Horizontal Axis machines are further re-classified as up-wind and down-wind turbines, if the faces of blades are in front of the wind and behind the wind respectively. Most of today's commercial wind machines are three blades up-wind horizontal axis wind turbines due to their aerodynamic stability, Low cut-in wind speed and high power coefficient .However the design of Horizontal Axis Wind Turbines are more complex and expensive since the generator and gearbox of these turbines are to be placed over the tower [47].

The principal components of a modern HAWT are tower; rotor which is the prime mover, nacelle and the yaw, the nacelle is the houses of the gear box and the generator. The tower carries the main part of the wind turbine and keeps the rotating blades at a height to capture sufficient wind power. The wind turbine rotor blades are turned against the wind direction by yaw mechanism. The gearbox is used to speed up the slower rotational speeds of the wind turbine to higher rotational speed which is suitable for the Electrical generator that converts the torque energy in to electrical energy through a shaft which connects the blades with the generator. A typical block diagram of a HAWT is shown in the fig.2.3.4 below.

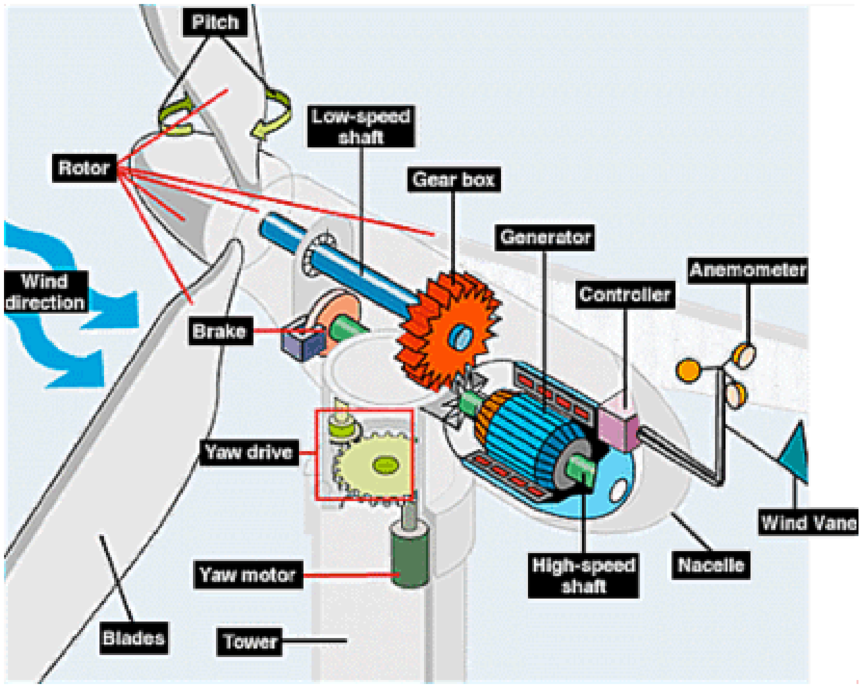


Figure 2-11 Components of wind turbine [61]

A small size, three bladed, up-wind, horizontal axis wind turbine type is selected for this study. Because of their aerodynamic stability, low cut-in wind speed and high power coefficient. And the specification of the selected wind turbine is shown in section 4.2.1.3.

### 2.3.7 Wind Turbine Generators

An electrical generator is one of the most important components of a wind energy conversion system that converts mechanical energy into electrical energy through the interaction of electromagnetic and electrostatic fields. In contrast with the generators used in other conventional energy options, generator of a wind turbine has to work under fluctuating power levels. Generators are classified as either induction (asynchronous) generators or synchronous generators [18].

#### 2.3.7.1 Asynchronous generators (Induction generator)

Since the rotor speed of an induction generator is not synchronized, it is also called asynchronous generators. Asynchronous generator can be either wound rotor or squirrel-cage type that operates in principle of electromagnetic induction. It should be coupled to grid system before it starts-up since it draws the excitation current from the grid and it absorbs the reactive energy by its own magnetism. Using a bank of capacitors can compensate for the absorbed reactive energy. It cannot generate if it is disconnected from the autonomous grid because of unable of providing its own excitation current. Regarding this, voltage regulation in induction generators is difficult [18].

In contrast, induction generator is simple, strong in construction, relatively inexpensive and need minimum maintenance as compared to synchronous generator. It can be used in very small stand-alone applications as a cheap solution when the required quality of the electricity supply is not very high. The application induction generator is limited for wind application where wind speed at the selected site is highly variable [18].

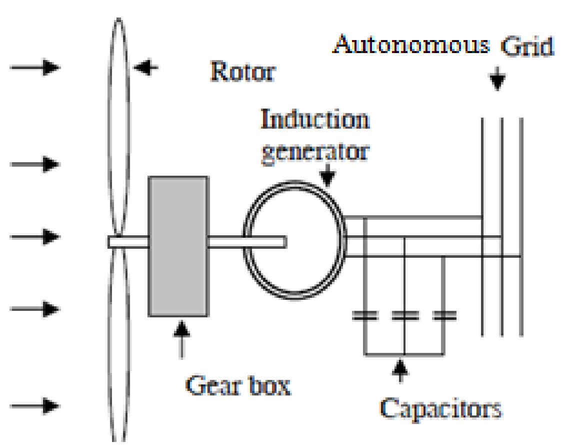


Figure 2-12 Fixed speed wind turbine [47]

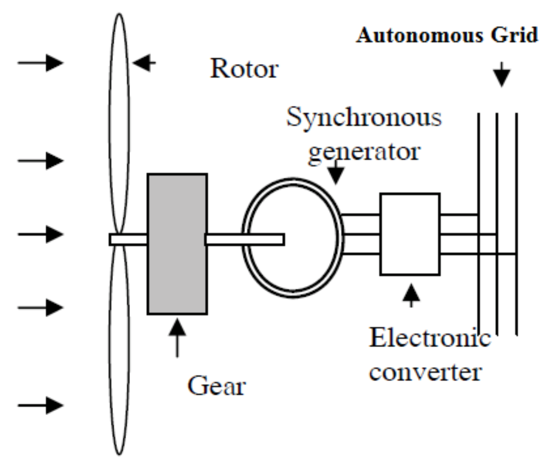


Figure 2-13 Variable speed wind turbine [47]

**2.3.7.2 Synchronous generators**

In the case of synchronous generator, the rotor and magnetic field rotates at the same speed. The stator and rotor have the same number of poles. Synchronous generator is provided with a DC electric or permanent magnet excitation system together with a voltage regulator to control the output voltage before the generator is connected to the grid. When the generator is connected to the autonomous grid it supplies the reactive energy required by the power system. Since excitation is not grid-dependent synchronous generators can run isolated from the grid and produce power. Synchronous generator is more expensive than asynchronous generators if its generation capacity is below 1 MW. And is used in power systems where the output of the generator represents a significant proportion of the power system load [18].

#### 2.3.7.3 Generator Rotational Speed

The speed of a generator which is directly connected to a grid is constant, and dictated by the frequency of the grid. In the case of the synchronous generator, the speed is set by the grid frequency and the number of pairs of poles of generators. The relationship between the rotational speed of Synchronous generator and frequency is governed by the formula below

$$N_s = \frac{60f}{P_{pole}} \qquad (2.3.8)$$

Where $N_s$ is the synchronous speed, f is the line frequency and

$P_{pole}$ is the number of poles pairs.

The number of poles means the number of coil sets in the stator of the generator which the electric power is generated in. And two poles make one pole pair. When the number of pole pairs is doubled in the stator of a synchronous generator, the speed will decreased to half. The number of poles will be decided by the construction of generator.

The speed of the asynchronous generator varies with the turning force or torque applied to it. It has a slightly softer connection to the network frequency than the synchronous generator, as it allows a limited amount of slip.

### 2.3.8 Wind Turbines Power Regulation Mechanism

For safety operating conditions the wind turbine is designed to operate at a certain level. Power generated by the rotor is regulated to its rated level between the rated and cut-out wind speeds. Otherwise, the power would have been increased with wind speed. If the wind turbine is desired to harness the power at its full capacity even at high velocity it has to be designed to accommodate higher levels of power output. This implies that, the system would require stronger transmission and bigger generator. In contrast, probability for such high wind velocities is very low in most of the wind regimes. Consequently, it is not economical to over design the system to accommodate the extra power available for a very short period of time. For this reason all wind turbines are designed with some sort of power control. There are three most commonly used types of power control: Stall Control, Pitch Control and Active stall regulation.

#### 2.3.8.1 Stall Control Mechanism

In stall control the blades are bolted onto the hub at a fixed angle. Stall control is simplest, most robust and cheapest control method is the stall control. The design of the rotor aerodynamics causes the rotor to lose power when the wind speed exceeds a certain level which limits the aerodynamic power on the blades. The twist and thickness of the rotor blade is not uniform along its length so that turbulence occurs behind the blade if the wind speed becomes too high. At higher speeds power output minimum because the turbulence causes some of the wind's energy to be shed [36].

#### 2.3.8.2 Pitch Control Mechanism

In pitch control mechanism the rotor blades are rotated around their longitudinal axis. The angle of the rotor blades can be actively adjusted by the machine control system. This is known as pitch control. The control system is usually operated using hydraulics or electric stepper motors. Depending on the output power an electronic controller sends a signal to the blade pitch mechanism in order to turn the rotor blades out of the wind to the actual degree required and to keep the rotor blades at the optimum angle for maximized output at all wind speeds[22] [53].

#### 2.3.8.3 Active Stall Controlled Wind Turbines

Larger wind turbines, 1MW and above are constructed with an active stall power control mechanism. In active stall regulation mechanism, the machine is equipped with a program that controls the blades much like a pitch-controlled machine at low and higher wind speeds, In order to get a reasonably large torque at low wind speeds, the machine is programmed to pitch its blades. If the machine is about to reach its rated power then the machine also pitches its blades to increase the angle of attack of the blades forcing the blades to go into a deeper stall and waste the excess energy of wind. Active stall mechanism can control power output more accurately than that of stall control mechanism [22] [53].

### 2.3.9 Power and Energy Output of Wind Turbine

#### 2.3.9.1 Wind Energy Content and Extracted Wind Power

The amount of energy extracted by the rotor depends on the density of the air, the rotor area, and the wind speed. The kinetic energy in the wind depends on the density of the air since the kinetic energy of a moving body is proportional to its mass. At normal atmospheric pressure and temperature of $15^0$C, the density of air is 1.225 kg/$m^3$. The heavier the air, the more energy is received by the turbine. The rotor area also decides the magnitude of the energy that a wind turbine is able to harvest from the wind. If the rotor diameter is doubled, the rotor area will become four times that of the former one. This means that four times as much power output from the rotor will also be obtained. In addition the energy in the wind is proportional to the cube of the wind speed as it is shown in the equations below [26].

The theoretical wind power is defined as

$$P_t = \frac{1}{2}\rho A_T V^3 \qquad (2.3.9)$$

Where v is the wind speed, $\rho$ is the density of the air (kg/m$^3$) that passes around the rotor area and $A_T$ is swept area of the rotor. A wind rotor cross –sectional area is shown in the figure 2.9**.**

### Extracted wind power

Power is the function of air density (ρ), rotor area ($A_T$) and air stream velocity .The effect of wind velocity is more dominant since it has cubic relation with the power. A wind turbine cannot extract power completely from the wind. When the wind stream passes the turbine, a part of its kinetic energy is transferred to the rotor. The real exploitable power of the wind using the rotor blades is obtained by subtracting the downstream wind power from upstream wind power using equation below [39].

$$P_m = \frac{1}{2} \text{mass flow rate per second } (V_i^2 - V_o^2) \qquad (2.3.10)$$

Where $P_m$ is mechanical power extracted by the rotor and V and $V_o$ are upstream wind velocity at the entrance of the rotor blades and downstream wind velocity at the exit of the rotor blades respectively.

The turbine output power, extracted by the rotor which drive the electrical generator can be rewrite as shown below

$$P_m = \frac{1}{2}\rho * A * V^3 \left(1 + \frac{Vo}{V}\right)\left(1 - \frac{Vo}{V}\right)^2 \qquad (2.3.11)$$

$$P_m = \frac{1}{2}\rho * A * V^3 C_P \qquad (2.3.12)$$

Where $C_P = \left(1 + \frac{Vo}{V}\right)\left(1 - \frac{Vo}{V}\right)^2$ and it is known as power coefficient of the rotor or rotor efficiency

The value of $C_p$ depends on the ratio of the downstream to the upper stream wind speed. The graph of Cp versus Vo/V indicates that the $C_p$ max value is 0.59 when Vo/V is one third (1/3).Thus the theoretical maximum value of cp is 0.59, where as the value of Cp for practical design is below 0.5 for high speed wind turbines.

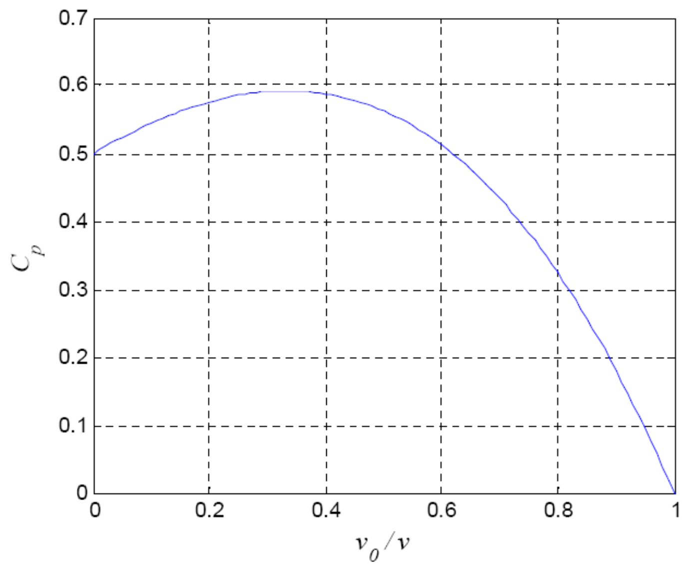


Figure 2-14 Theoretical rotor efficiency VS. $v_0/v$ ratio [68]

# CHAPTER THREE

## 3 Energy Need and Available Resources Assessment of a Village

### 3.1 Description of the Village and Data Collection

Hamsa Gasha is the selected off-grid remote rural village for this study. It is a small village found in the Arsi Zone, Oromia Regional State. The village is located at Latitude 7°47' N and Longitude 39°03'E and it is about 30 to 40 kilometers away from Assela town in South West direction. According to 2007 Population and Housing Census of Ethiopia Hamsa Gasha village has a total population of 3,102 people out of which 1,604 are male and 1,498 are female and 586 households [Central Statistical Agency]. There is only one primary school, two churches, one Mosque, and one health center in the village. There is a river called Ketar that passes through the village. Figure 3.1 shows the location of the village on the map.

In spite of having significant renewable energy resources such as hydro and wind, the village does not have access to electricity. Different areas have different types of energy source available for converting into electricity. The best solution to provide electricity to the village may be to integrate micro hydro with wind energy together to provide electricity.

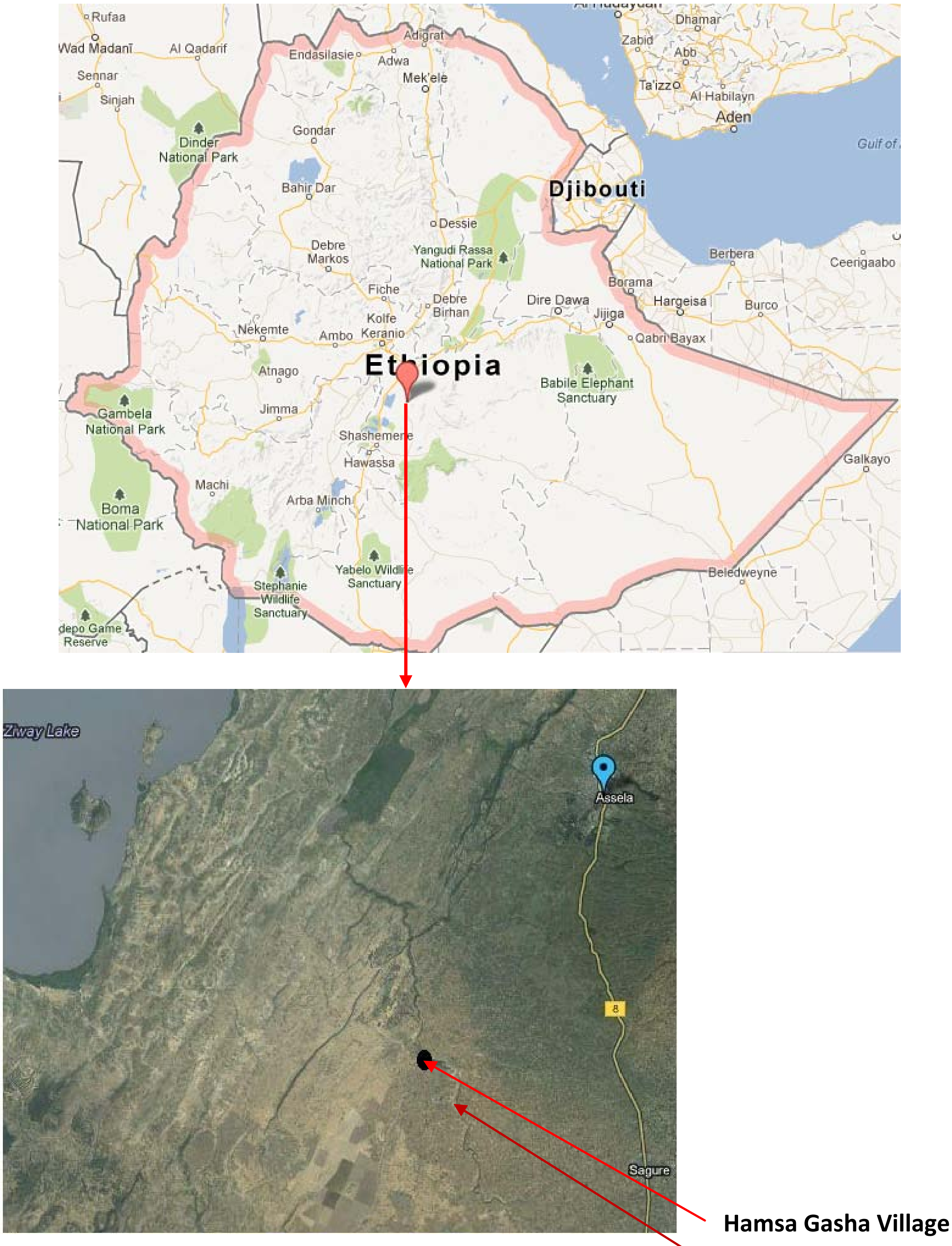


Figure 3-1 Location of the village on the Map [Google earth]

**Primary and Secondary Data Collection**

Primary data are those collected by the direct participation of the researcher conducting the research. During field survey, primary data such as the head of the river, the number of churches, schools and health centers of the study area are collected. The head of the river is determined by direct measurement using GPS, where the other mentioned data are collected through interview with the local people who live nearby the river.

For the village around Ketar River, called Hamsa Gasha there are 586 households. This area is suitable for irrigation. These irrigating lands are supplied by transporting water a long distance away from the farm lands using old methods. Some of the peasants use diesel pumps. Therefore, in this area, 7 water pumps with 2kW rated power each are assumed to be used for irrigation purpose.

Secondary Data is a data that is not collected by the researcher, and it is not collected for his/her own purpose and objective. Secondary Data may have been collected by other researchers or by concerned institutions that are involved in collecting data. Hence it may be hard to get exactly the type of data needed by the researcher [49].

Secondary Data that are necessary for this thesis are wind speed, flow rate of river, population size and numbers of households of the selected site and costs of the energy equipments. They are collected from different organizations and websites. Stream flow rate and wind speed data are collected from Ministry of Water and Energy and National Meteorological Agency respectively. Whereas the population size and numbers of households are taken from the website of the Ethiopian Central Statistical Agency.

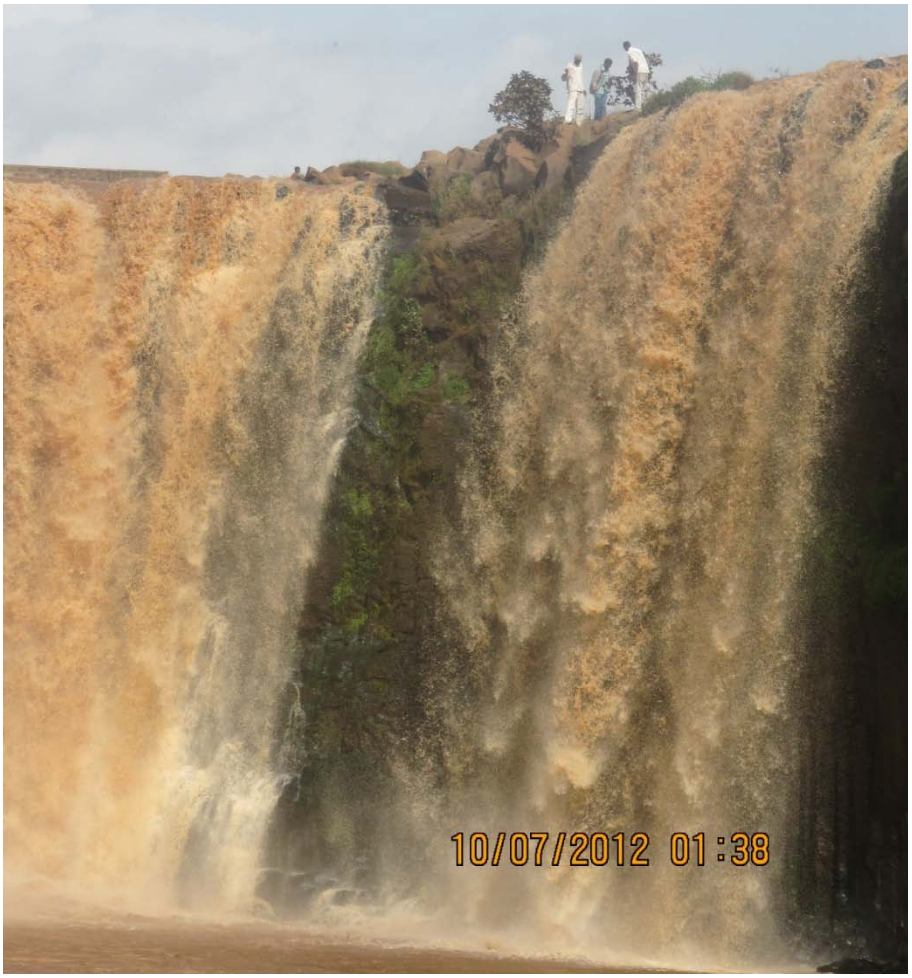


Figure 3-2 Surveying the head of the micro hydro at the selected site

## 3.2 Energy Need Assessment and Scheduling of the Village

Electric power is the most versatile type of energy source that can be used to fulfill any kind of energy demand. In remote rural areas the demand for electricity is not as high as urban areas. The electrical energy supplied by the hybrid system is assumed to be applied by small household appliances, such as lighting, entertainment in the village. The basic energy load in these areas can be categorized as primary load and secondary load [15].

A primary load is the electrical energy demand that the power system designed must serve according to a particular schedule or specified time, and used for applications such as household appliances televisions, radio, and lighting of the domestic houses and public services. On the other hand secondary load is also known as a deferrable load, an electric demand that can be served at certain period of time. Secondary load met only after the primary load has been satisfied except under special circumstances. It is assumed that the exact timing is not important. The deferrable load includes activities like pumping water, charging batteries and heating water. Due to the nature of the load, it also determines the energy storage capacity of a system [45].

The basic energy requirements of the village can also be, classified into three. These are community, domestic and agricultural load. Domestic load is used for the application of lighting, cooking, televisions, and radio, in each households .The community load includes schools, churches, mosques and health center. The electrical energy used for lighting and megaphone in school, churches and mosque is categorized as a community load and the electrical energy for lighting and miscellaneous load in school is also public load. The load used to operate refrigerator and lighting in the health center are also public load. Agricultural load is secondary load that is used to drive irrigation machinery and water pumping for drinking water purpose [45].

The houses of Hamsa Gasha village are assumed to divide in to two classes, as large house and small house. Due to the population and economical growth rate the 586 households of the village definitely increase to a certain figure. The current numbers of households of the village are approximated to be 660, with help the annual population growth rate of the country which is indicated in figure 3.3 below. And the energy demand of the village will be estimated based on current numbers of households. It is facts that all the people of the village have not the same economical status i.e. some of the households are relatively rich and most of them are comparatively poor. For instance majority of the households may not offer the electricity cost if they use electric oven ('Enjera Mitad'). Hence out of the 660 houses of the village 180 of them are categorized under large house and the rest are assumed as small houses.

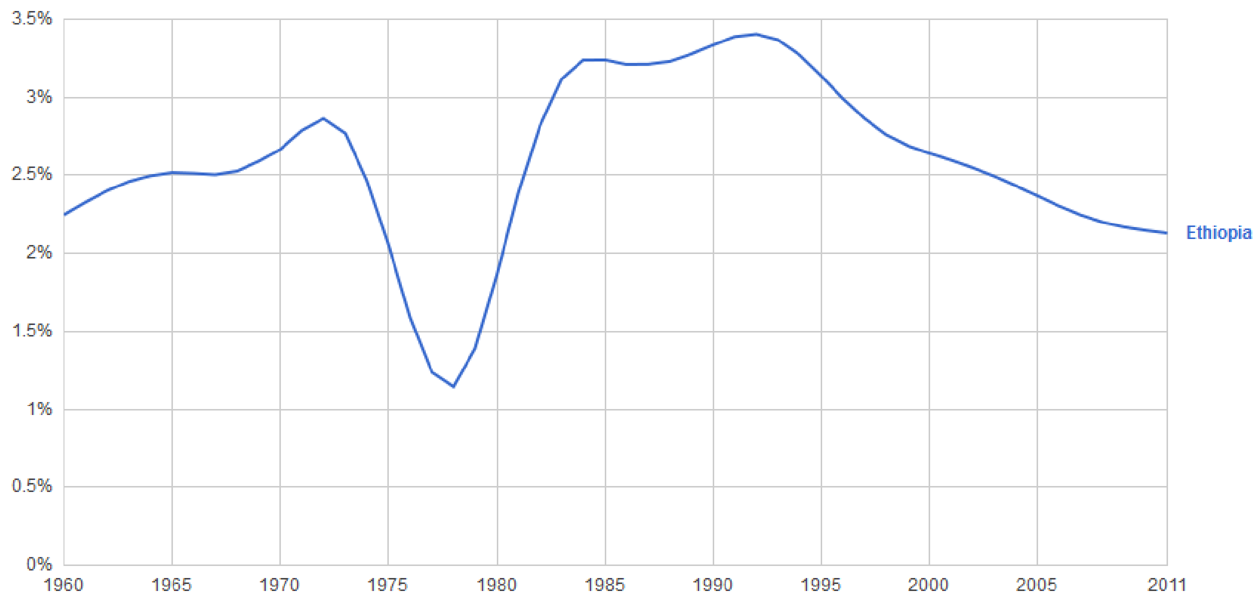


Figure 3-3 Population growth rate graph of Ethiopia [World Bank]

The planned electrical load for each small household includes two 11W compact fluorescent lamps (CFLs) to be used between 18:00 and 23:00, a 11W radio receiver operated for 6 hours during working days and 11 hours during weekends, a 70W rated 14' color TV working between 18:00 and 23:00 every day and 11:00-23:00 during weekends. Similarly the large households assumed to have three 11W CFLs, a radio 11W receiver, a 70W 14' color TV and 3000W rating electric oven ('Enjera Mitad') for two hours once every three day.

The primary school consists of 8 classrooms and each classroom will be installed with four 11W CFLs) .In addition four 11 W CFLs are assumed for office light and two another 11W CFLs are also considered for external lighting. Evening classes are conducted from 18:00 to 21:00.The school needs another 200W load for office loads such as computer and printer to be operated between 9:00 and 4:00.

Likewise, the following electric loads are considered for health center. Six 11W CFLs for rooms and external lighting, a 200W rated refrigerator working for 24 hours, a 20W capacity microscope and a 1.5 kW rated water heater operated for four hours per day.

Small flour milling machine with rated power of 7.5KW and milling capacity of 350kg/hour is considered for the community. The flour mills is assumed to operate from 8:00 to 12:00 and

14:00 to 18:00. Seven pumps with rated power of 2kW each are also selected for irrigation purpose of the village, that are operated each for 8 hours daily.

The electrical energy requirements of the village vary from season to season and weekend to working days. The primary school is not conducted during weekends and summer i.e. July and August. In addition, it is important to note that the irrigation pumps are not used during the rainy seasons, July, August and September. Because of the religious concern of the people, it assumed that flour mill and water pumping system for irrigation are not also operational during weekends.

The table 3.1 below shows estimation of each appliance's rated power, its quantity and the duration hours of use by each house, church, mosque, health center, pump and flour mill and school in a single day. The miscellaneous load is for unknown loads in each category such as cell phone charging. Details calculation of the village loads for working days, weekend and summer are given in appendix A.

Table 3-1 Village Load Estimation of Working Days

| Service type | Load type | Rated power(W) | quantity | duration(hrs) | Energy(Whrs/day) | Total energy(KWhr/day) of the village |
|---|---|---|---|---|---|---|
| Small houses | Light | 11 | 2 | 5 | 165 | 52.8 |
| | TV | 70 | 1 | 9 | 630 | 302.4 |
| | Radio | 10 | 1 | 11 | 110 | 52.8 |
| | Miscellaneous | 30 | 1 | 24 | 720 | 345.6 |
| Sub total | | | | | | **753.6** |
| Large house | Light | 11 | 3 | 5 | 165 | 29.7 |
| | TV | 70 | 1 | 9 | 630 | 113.4 |
| | Radio | 10 | 1 | 11 | 110 | 19.8 |
| | Enjera Oven | 3000 | 1 | 2 | 6000 | 360 |
| | Miscellaneous | 30 | 1 | 24 | 720 | 129.6 |
| Sub total | | | | | | **652.5** |
| Agricultural | pump | 2000 | 7 | 8 | 112000 | 112 |
| flour mill | mill | 7500 | 1 | 8 | 60000 | 60 |
| Sub total | | | | | | **172** |

Public Load

| Service type | Load type | Rated power(W) | quantity | duration(hrs) | Energy(Whrs/day) | total Energy (kWhr/day |
|---|---|---|---|---|---|---|
| School | Light | 11 | 38 | 4 | 1936 | 1.672 |
| | Office load | 200 | 1 | 9 | 720 | 1.8 |
| | Miscellaneous | 50 | 1 | 24 | 1200 | 1.2 |
| Sub total | | | | | | **4.672** |
| Churches | lighting | 11 | 20 | 7 | 1848 | 1.54 |
| | megaphone | 30 | 8 | 8 | 1680 | 1.92 |
| | miscellaneous | 40 | 1 | 24 | 960 | 0.96 |
| Sub total | | | | | | **4.42** |
| Mosque | lighting | 11 | 10 | 8 | 726 | 0.88 |
| | megaphone | 30 | 4 | 6 | 720 | 0.72 |
| | miscellaneous | 40 | 1 | 24 | 960 | 0.96 |
| Sub total | | | | | | **2.56** |
| health center | lighting | 11 | 6 | 13 | 858 | 0.858 |
| | microscope | 20 | 1 | 8 | 160 | 0.16 |
| | refrigerator | 200 | 1 | 24 | 1920 | 4.8 |
| | water heater | 1500 | 1 | 4 | 4000 | 6 |
| | miscellaneous | 50 | 1 | 24 | 1200 | 1.2 |
| Sub total | | | | | | **13.018** |
| Daily energy need(kWh) | | | | | | **1602.77** |

The estimated hourly loads of the summer and other season of the year are given in Figure 3.5 and 3.4 respectively.

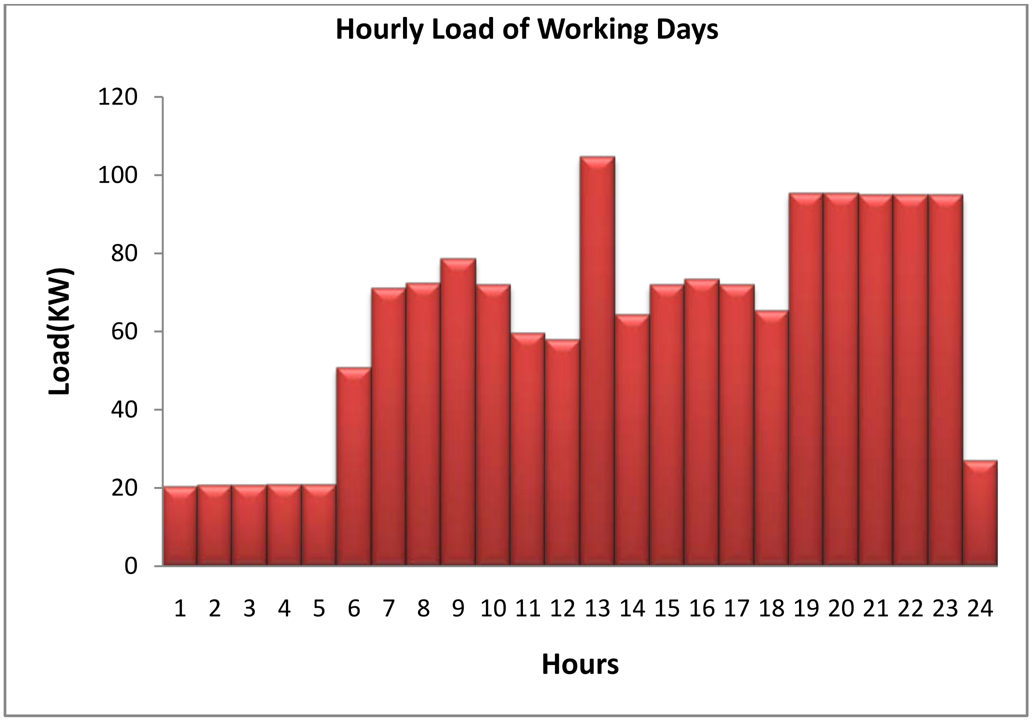


Figure 3-4 Daily load of Hamsa Gasha village for week days

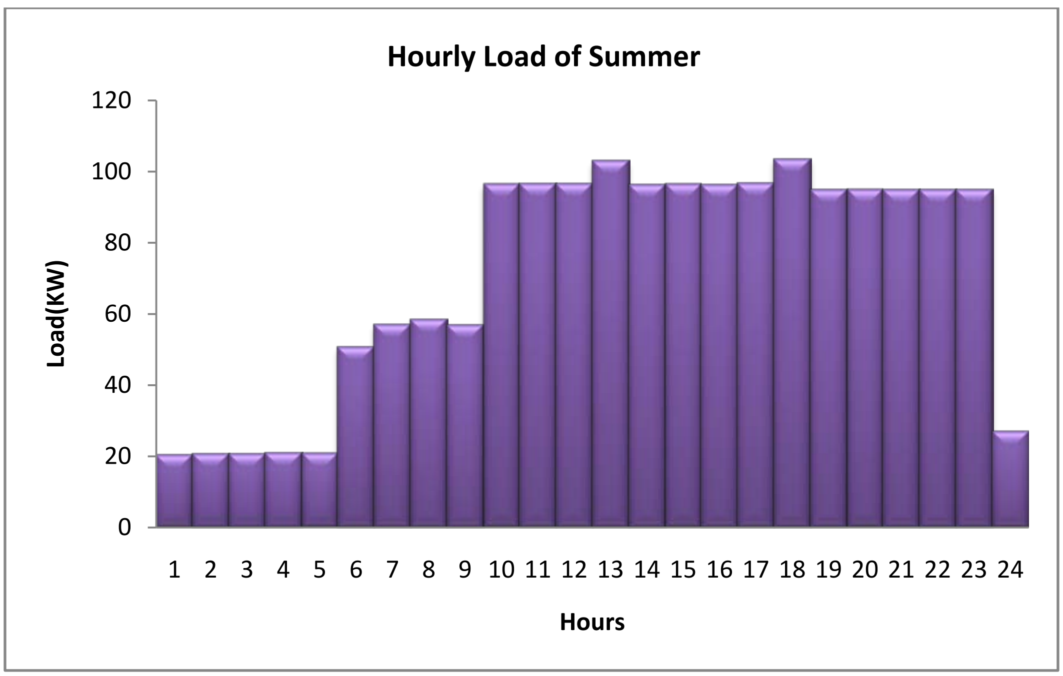


Figure 3-5 Lload demand of Hamsa Gasha village for a day in summer (July- September)

In the above graph the total estimated peak load indicated is not the actual peak load that will be seen by the system, because all the loads allocated for a certain time period might not be switched on at the same time. The daily load distribution of the village varies largely across the day as shown in Figure 3.4 and 3.5.The variation of load from time to time has resulted because all appliances are not switched on at the same time. The average daily energy demand of the site is about 1520 kWh and the yearly energy demand is estimated as.

$$\text{Annual average required energy} = 1520\frac{\text{kWh}}{\text{day}}\text{x}30\frac{\text{day}}{\text{month}}\text{x}12\frac{\text{month}}{\text{year}} = 547.2\text{MWh/year}$$

## 3.3 Wind Energy Resources Assessment of the Village

The monthly average wind speed data resource used for Hamsa Gasha village which is located at a 7°47' N latitude and 39°03' E longitude, was obtained from NASA Surface Meteorology is presented in table 3.2 below. The annual average wind speed for the location is 3.1 m/sec at the anemometer height of 10 meters. This data can be extrapolated to the selected wind turbine height (40meter) using equation 2.3.5. The value of the surface roughness length ($Z_0$) is taken as 0.1. Table 3.2 summarizes the wind speed at 10 m, 40 m and 50 m heights.

Table 3-2 Monthly average wind speed of the site [NASA]

| Average Wind Speed (m/s) | Month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan | Feb | Mar | Apr | May | Jun | July | Aug | Sep | Oct | Nov | Dec |
| **V(m/s)@10m** | 3.6 | 3.2 | 3.1 | 3.1 | 3.0 | 3.0 | 2.7 | 2.6 | 2.6 | 2.9 | 3.3 | 3.5 |
| **V(m/s)@40m** | 4.7 | 4.2 | 4.0 | 4.0 | 3.9 | 3.9 | 3.5 | 3.4 | 3.4 | 3.8 | 4.3 | 4.6 |
| **V(m/s)@50m** | 6.3 | 5.6 | 5.4 | 5.4 | 5.3 | 5.3 | 4.7 | 4.6 | 4.6 | 5.1 | 5.8 | 6.1 |

### 3.3.1 Wind Speed Frequency Distribution of the Village

The monthly average wind velocity $V_{av}$ of a regime can be determined using the Weibull distribution.

$$V_{av} = \int_0^\infty v f(v)\, dv \qquad (3.1)$$

Substituting for f($v$) from the equation 2.3.1 in section 2.3.2, the above equation can be rewritten as follows.

$$V_{av} = \int_0^\infty v \frac{k}{c}\left[\frac{v}{c}\right]^{k-1} e^{-(v/c)^k} dv = k\int_0^\infty \left[\frac{v}{c}\right]^{k} e^{-(v/c)^k} dv \qquad (3.2)$$

Let, $x = \left(\frac{v}{c}\right)^k$

Hence, $dv = \frac{c}{k} x^{\left(1/k - 1\right)}$

Substituting the value of d$v$ in to the above Eq. (3.2), we get the following equation

$$V_{av} = c\int_0^\infty e^{-x} x^{1/k} dx \qquad (3.3)$$

This is in the form of the standard gamma function, which is given by

$$\Gamma_n = \int_0^\infty e^{-x} x^{n-1} dx \qquad (3.4)$$

From the above Eq. (3.4), the average velocity can be expressed as

$$V_{av} = c\Gamma\left(1 + {}^{1}/_{\mathrm{k}}\right) \qquad (3.5)$$

Evaluating the above expression and rearranging for k=2, the scale factor c can be approximated

$$c = \frac{2V_{av}}{\sqrt{\pi}} \qquad (3.6)$$

The probability density graph of a wind regime can be plotted using equation 2.3.1 after determining the values of k and c of the site. Figure 3.6 is the probability density graph of the village at turbine hub height (40m) plotted by HOMER.

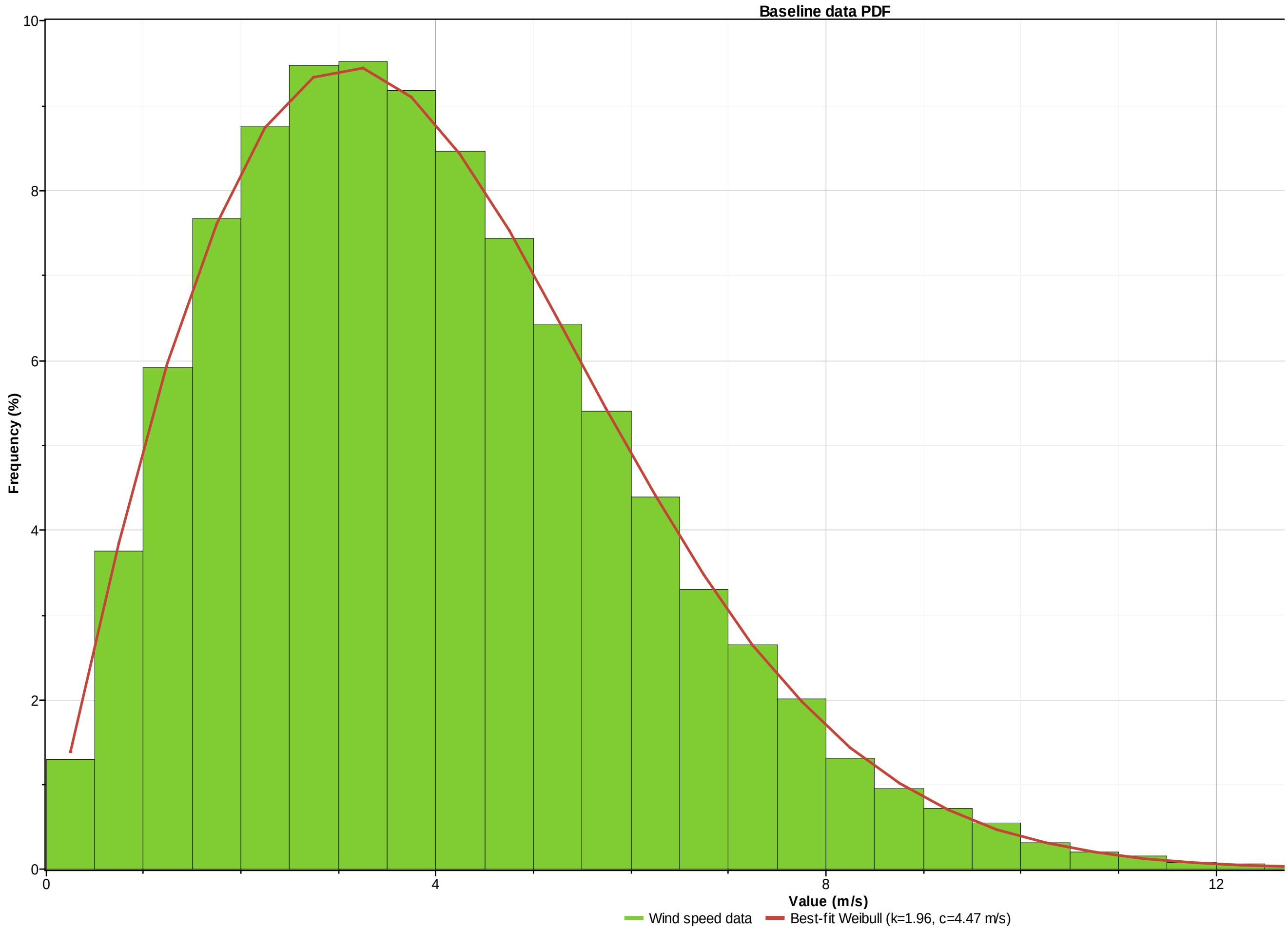


Figure 3-6:- Probability density VS wind speed at turbine hub height of Hamsa Gasha village

### 3.3.2 Wind Power Density Estimation of the Village

Wind energy density ($E_D$) is the energy available at a particular place for a unit rotor area and time. One of the preliminary steps in the planning of a wind energy project is to evaluate the energy available in the wind regime prevailing at a site [47].

For a unit area of the rotor, power available P in the wind stream of velocity V is

$$P = \frac{1}{2}\rho_a V^3 \qquad (3.7)$$

The total energy contributed by all possible velocities in the wind regime, available for unit rotor area and time may be expressed as.

$$E_D = \int_0^{\infty} P\, f(v)\, dv \qquad (3.8)$$

Substituting, the values of P and $f(v)$ from equations, 3.7 and 2.3.1 respectively the equation below is obtained.

$$E_D = \frac{k\rho_a}{2c^k}\int_0^\infty V^{(k+2)} e^{-(v/c)^k}\, dv \qquad (3.9)$$

Taking $x = (v/c)^k$

Equation 3.11 can be rewritten as shown below.

$$E_D = 1/2\, c^3 \rho_a \int_0^\infty x^{3/k}\, e^{-x}\, dv \qquad (3.10)$$

Applying the standard gamma integral, we get

$$E_D = 1/2\, c^3 \rho_a\, \Gamma(3/k + 1) \qquad (3.11)$$

For k=2 the above equation becomes

$$E_D = 1/2\, c^3 \rho_a\, \frac{3}{4}\sqrt{\pi} \qquad (3.12)$$

Substituting for c from equation 3.6 in to equation 3.12, the average power density is calculated as follows.

$$E_D = \frac{3}{\pi}\rho_a V_{av}^3 \qquad (3.13)$$

The available energy for the unit area of the rotor, over a given period time (t), can be estimated using the expression below.

$$E_t = \frac{3}{\pi}\rho_a V_{av}^3 * t \qquad (3.14)$$

The wind power densities values of the village indicated in the table 3.4 is calculated using equation 3.13. The table clearly shows that the power density varies from month to month. The maximum power density occurs in January, whereas the minimum power densities are found twice, in August and September.

Table 3-3 Wind power density of Hamsa Gasha Village

| **Month** | **Monthly average wind speed V(m/s)** | | **Power density $E_D$ (W/m$^2$)** | |
|---|---|---|---|---|
| | at 40m height | at 50m height | at 40m height | at 50m height |
| **Jan** | 4.7 | 6.3 | 120.2 | 295.3 |
| **Feb** | 4.2 | 5.6 | 84.4 | 207.4 |
| **Mar** | 4.0 | 5.4 | 76.7 | 188.6 |

| | | | | |
|---|---|---|---|---|
| **Apr** | 4.0 | 5.4 | 76.7 | 188.6 |
| **May** | 3.9 | 5.3 | 69.5 | 170.9 |
| **Jun** | 3.9 | 5.3 | 69.5 | 170.9 |
| **July** | 3.5 | 4.7 | 50.7 | 124.6 |
| **Aug** | 3.4 | 4.6 | 45.3 | 111.3 |
| **Sep** | 3.4 | 4.6 | 45.3 | 111.3 |
| **Oct** | 3.8 | 5.1 | 62.8 | 154.4 |
| **Nov** | 4.3 | 5.8 | 92.6 | 227.5 |
| **Dec** | 4.6 | 6.1 | 110.4 | 271.4 |
| Monthly annual average | **4.0** | **5.4** | **75.4** | **185.2** |

Estimates of wind power density are presented as wind class, ranging from 1 to 7. Class 1 wind sites have low wind power potential, while site under class 7 acquire high power potentials. Based on the specified Table 3.3 and 3.4 annual average wind speed and power density distribution of the village are categorized in first wind class which is low. But the wind class of the village for each month varies from first to second wind class.

Table 3-4 Wind class category by wind speed and power density [Wikipedia]

| Class | 10m | | 30 m | | 50 m | |
|---|---|---|---|---|---|---|
| | Wind power density($W/m^2$) | Wind Speed m/s | Wind power density($W/m^2$) | Wind Speed m/s | Wind power density($W/m^2$) | Wind Speed m/s |
| 1 | 0 - 100 | 0 - 4.4 | 0 - 160 | 0 - 5.1 | 0 - 200 | 0 - 5.6 |
| 2 | 100 - 150 | 4.4 - 5.1 | 160 - 240 | 5.1 - 5.9 | 200 - 300 | 5.6 - 6.4 |
| 3 | 150 - 200 | 5.1 - 5.6 | 240 - 320 | 5.9 - 6.5 | 300 - 400 | 6.4 - 7.0 |
| 4 | 200 - 250 | 5.6 - 6.0 | 320 - 400 | 6.5 - 7.0 | 400 - 500 | 7.0 -7.5 |
| 5 | 250 - 300 | 6.0 - 6.4 | 400 - 480 | 7.0 - 7.4 | 500 - 600 | 7.5 - 8.0 |
| 6 | 300 - 400 | 6.4 - 7.0 | 480 - 640 | 7.4 - 8.2 | 600 - 800 | 8.0 - 8.8 |
| 7 | 400 – 1000 | 7.0 - 9.4 | 640 -1600 | 8.2 - 11.0 | 800 - 2000 | 8.8 -11.9 |

### 3.3.3 Wind turbine Selection

Wind turbines have been selected using different criteria such as the wind turbine cost, type of current generated (AC or DC), cut-in wind speed, and type of application. Even though the primary criterion for the selection of the wind turbine is its cost, the cut-in wind speed criterion is used as main criteria for this research because of the following reasons. The actual price of each type of wind turbine is difficult to get on manufacturers websites. In addition, since the wind class of the selected village is low as explained in section 3.3.2, it is fair to use the cut-in wind speed criterion.

Based on the selection criteria mentioned above, different small wind turbines have been tested by running the simulation several times. Among those tested for simulation types of wind turbines the power curve of five different types of turbines are indicated in the graph below. The power curve is normally provided by the turbine's manufacturer and it is a graph that represents the turbine power output at different wind speeds values. Based on the power curve of wind turbines, all turbine types have zero power output between 0 and 2 m/s wind speed. This happen because the insufficient kinetic energy in the wind to rotate the wind turbine rotor.

The cut in wind speeds of Fuhrländer 30, BWC XL.50/14 and Eoltec Chinook 17-65 wind turbines lies between 2 and 3m/s. Whereas the cut in wind speed of HY30-AD11 is 3m/s. Furthermore Entegrity eW15 wind turbine has highest cut in wind speed compared to the others i.e. 4m/s. Eoltec Chinook 17-65 type has been found to be the best in terms of the cut-in wind speed. In low wind class areas, wind turbines with lower start up wind speeds are recommended. And also the power curve of this turbine lies above the other nominated turbines as shown in the graph. As a result the selected wind turbine has highest annual energy production compare to the other four.

The rated output power of Eoltec Chinook 17-65 wind generator is 65 kW with operating parameters of cut-in, rated and cut-out wind speeds of 2.3 m/s, 11 m/s and 20 m/s respectively. Major technical data of this Wind Turbines including the power curve, are given in appendix B

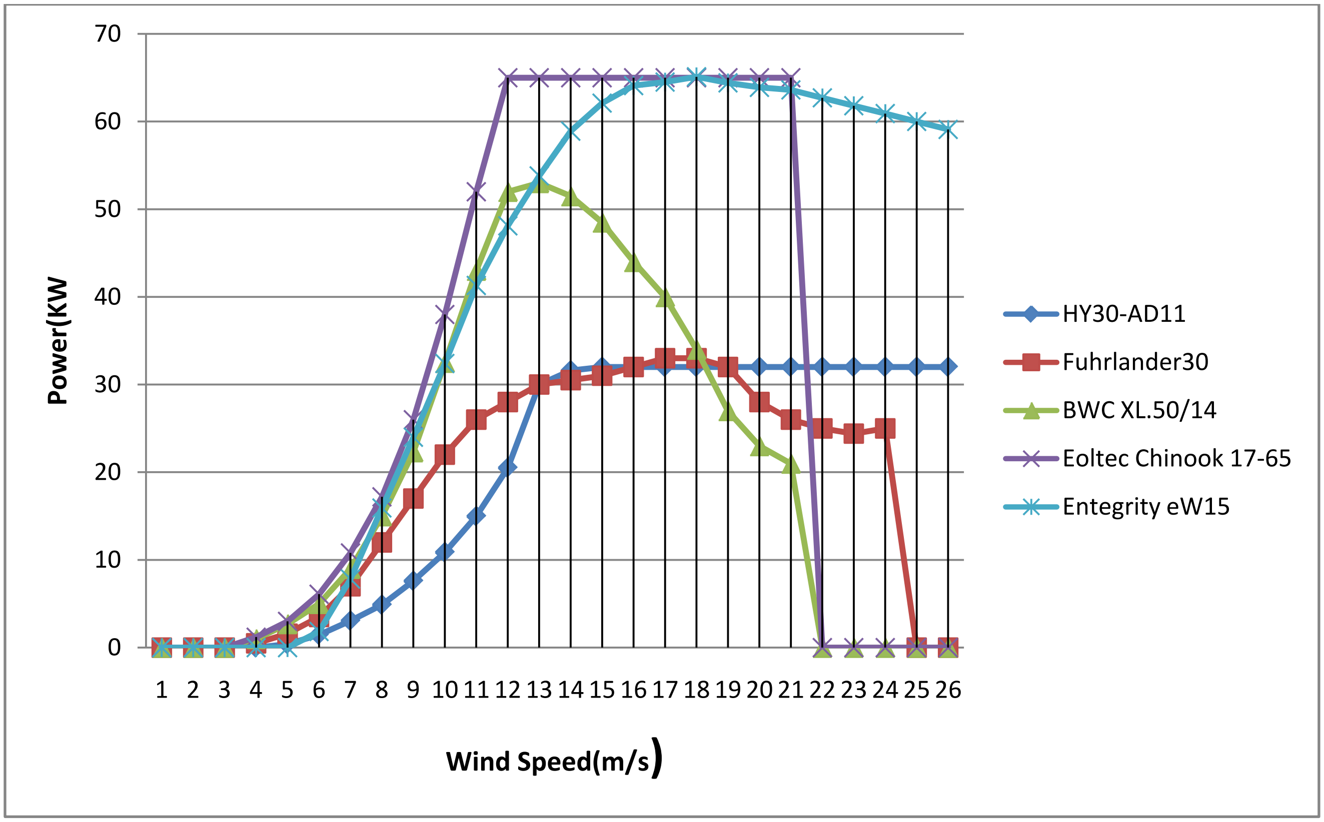


Figure 3-7 Power curves of different type wind turbines being simulated for the selected site

## 3.4 Micro Hydro Power Resources

### 3.4.1 Micro-Hydro Power Data Analysis

The daily average flow rate of **Ketar River** for the hydro resource data of 18 years was taken from the Ethiopian Water and Energy Minister. And the daily average flow rate of the river is changed in to monthly average in order to make suitable for the input of HOMER software. The gross head potential of the selected site is measured as 20 meter.

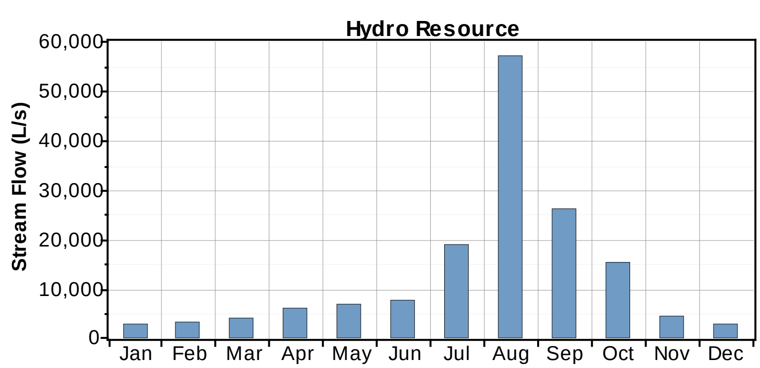

Figure 3-8 Micro hydro energy resource of the site (Ministry of Water and Energy)

### 3.4.2 Micro-Hydro Energy Estimation

Determining the hydropower potential of particular site is important for further action. The stream flow rate, head, existing constraints of the civil work and the end use type of the energy affects the hydropower potential [28].

### 3.4.3 Theoretical maximum power

To determine the hydropower output of a particular site requires two key parameters. These are the stream flow rate and head or vertical distance that the water drops. And the magnitude of the hydropower delivered depends mainly on the flow rate and head .The theoretical power output is expressed the equation below.

$$P_{theo.} = \gamma Q h_g, \qquad (3.15)$$

Where, $\gamma = \rho g$ $P_{theo}$= theoretical power (W), $\rho$ =density of water (kg/m$^3$), Q=flow rate (m$^3$/s) and $h_g$ = gross head (m)

**Effective head ($h_{ef}$)**

When water flows from the upper elevation to the lower one through medium channels and pipes, there is loss of energy as fractional drag and turbulence. As a result the gross head ($h_g$) will be higher than the net head or effective head ($h_{ef}$) and the effective Head ($h_{ef}$) is the difference between the gross head ($h_g$) and the head loss ($h_{loss}$).

$$h_{ef} = h_g - h_{loss} \qquad (3.16)$$

**System efficiency (η)**

The efficiency of the micro hydropower system is the combination the turbine efficiency $\eta_t$ or water wheel and generator efficiency $\eta_g$

$$\boldsymbol{\eta = \eta_g * \eta_t} \qquad (3.17)$$

Then the realistic output power is estimated as

$$\boldsymbol{P = \eta \gamma Q_{des} h_{ef}} \qquad (3.18)$$

Where, $Q_{des.}$ is the micro hydro power designed flow rate which is $0.5m^3/sec$.

The annual energy production of the micro hydro is estimated as follow.

$$\text{Annual energy production(Wh/year)} = \text{Power} * 365\,\frac{\text{days}}{\text{year}} * 24\,\frac{\text{hours}}{\text{day}}$$

# CHAPTER FOUR

# 4 Modeling of Micro Hydro-Wind Hybrid System for the Village

## 4.1 Introduction to Hybrid Power Systems and HOMER Software

### 4.1.1 Hybrid Power Systems

A hybrid system is a combination of one or more renewable and none renewable energy resources to generate energy or produce electricity .Renewable energy sources can complement each other [29]. And it may not be cost effective or not enough to implement a stand-alone small Hydro, PV system, wind turbine or any other power sources [35]. The most commonly used hybrid energy systems are solar, wind, biomass and hydro energy sources with other technologies such as batteries converter, diesel generator and grid. Hybrid power systems are new favorable system, especially for rural areas and weak grids, to provide enough electrical energy using different available renewable energies [20].

Hybrid renewable energy systems have great potential to provide higher quality and more reliable power to customers than a system based on a single resource. A system using a combination of these different sources has the advantage of balance and stability. Most renewable energy sources have a fluctuating energy output if they are subjected to generate energy independently. For instance, winds are usually relatively strong in winter and solar radiation and stream flow is higher in summer. Hybrid system provides stable output power from the resources and reduces the dependence of the output upon seasonal changes; additionally, it optimizes employment of the different renewable sources of energy available. In recent years renewable energy options have increasingly become the preferred solution for off-grid power generation, since they offers clean and efficient power that will in many cases be more cost-effective than sole diesel systems, due to the pressing environmental concerns and skyrocketing price of oil [42].

### 4.1.2 HOMER Software and Its Uses

The Hybrid Optimization Model for Electric Renewables (HOMER) is a computer model developed by the U.S. National Renewable Energy Laboratory (NREL). HOMER is used for several applications. One of the major functions of HOMER is to assist in the design of hybrid power systems for the effective appraisal of various renewable energy power generation technologies. It compares a wide range of equipment with different constraints and sensitivities to optimize the system design. HOMER models the physical behavior and life-cycle cost of a hybrid power systems that is the total cost of installing and operating the system over its lifetime. HOMER is suitable for designers to compare many different design options based on their technical and economic approach. It also assists in understanding and quantifying the effects of uncertainty or changes in the inputs. It provides optimized solutions of the power system's problem based on cost-effectiveness. HOMER helps to analyze the results of the optimization process in tables and graphs, after entering the information about components, loads and other important data [43].

HOMER allows modeling of grid-connected or off-grid hybrid power systems, generating AC and DC electricity and heat from various combinations of Solar PV Modules, wind turbines, small hydro, biomass power, micro-turbines, fuel cells, batteries, hydrogen storage and generators with various fuel options. Designing a micro power system with various design options and uncertainty issues in demand loads and fuel prices makes it a challenge. HOMER was designed to overcome these challenges and also the complexity of the RES being intermittent, seasonal, and non-dispatchable and having uncertain availability. Basically, HOMER executes three different tasks: Simulation, Optimization and Sensitivity analysis are the three major actions run by HOMER [40].

In the simulation process, HOMER models the performance of a particular hybrid power system configuration of each hour of the year to determine its technical feasibility and life-cycle cost. HOMER simulates the operation of a system by making energy balance calculations each hour in a year and compares the electric and thermal demand to the energy that the system can supply. And HOMER calculates the flows of energy to and from each component of the system. Generally simulation process has two successive operations. These are determining the feasibility of different loads and sources combinations and estimating the life-cycle cost of the system. The life-cycle cost (LCC) of the system is the total cost of installing and operating the system over its lifetime [43]. The LCC analysis of the hybrid system includes all expenses incurred over the life of the system considering the time value of money.

HOMER simulates several system configurations in order to decide the best system configuration. In the optimization process, HOMER selects one best optimal system configuration out of all configurations generated in the simulation process that fulfills all technical constraints and has the lowest life-cycle cost. The goal of the optimization process is to determine the optimal value of each decision variable that interests the modeler. The optimal sizes and numbers of each component that are used for HOMER to consider multiple sizes and numbers in its optimization process respectively are determine by the designer [40].

A sensitivity analysis helps to reveal how sensitive the outputs are to changes in the inputs. HOMER allows designers to enter a range of values for a single input variable. A variable for which the user has entered multiple values is called a sensitivity variable. Numerical input variable in HOMER that is not a decision variable can be a sensitivity variable. Such as the grid power price, the fuel price, the interest rate, load and renewable resource data are sensitivity variable. Sensitivity analysis helps assess the effects of uncertainty or changes in the variables over which the designer has no control [43].
"Figure 4.1 demonstrates the relationship between simulation, optimization, and sensitivity analysis. The optimization oval encloses the simulation oval to represent the fact that a single optimization consists of multiple simulations. Similarly, the sensitivity analysis oval encompasses the optimization oval because a single sensitivity analysis consists of multiple optimizations [43].

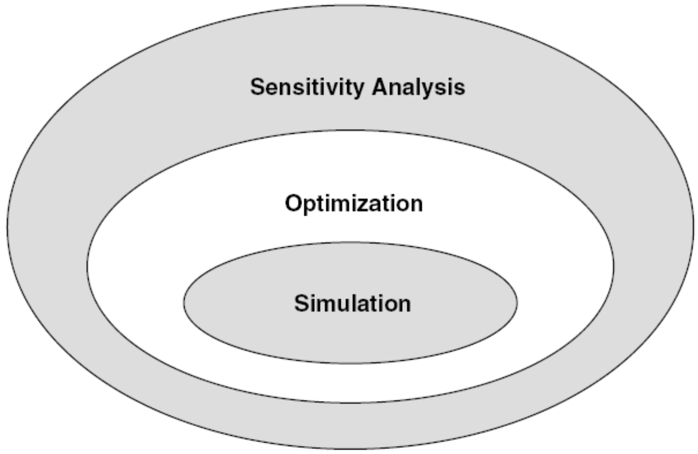


Figure 4-1 Relationship between simulation, optimization and sensitivity analysis [43]

## 4.2 Hybrid System Modeling With HOMER

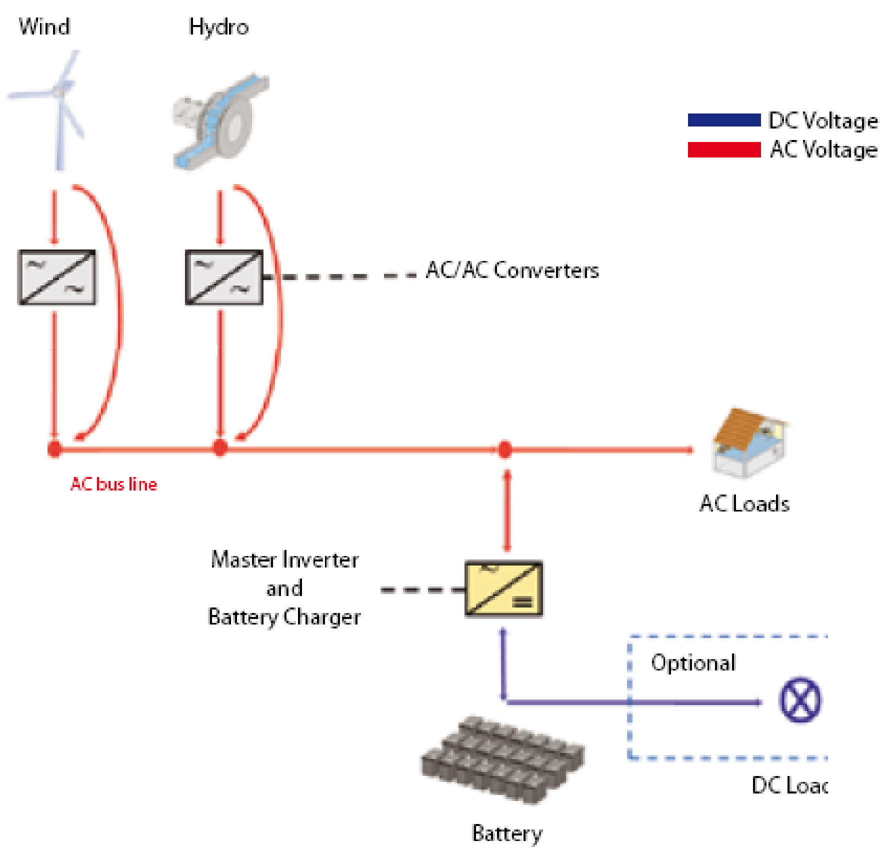


Figure 4-2 Hybrid of a Standalone System [6]

### 4.2.1 Input data to the Software

The significant variation of renewable energy source is not only from site to site, but also from time to time. Therefore the combination of two or more of these sources to supply energy for remote rural areas is economically feasible. Renewable energy sources such as wind and micro hydro are naturally available and intermittent; it is the best option to be combined into a hybrid system. The amount of power generated and the financial behaviour of the hybrid system are affected due to renewable energy sources deviation. Hence an accurate modeling of the RES is required to remove these problems. And this section explains the modeling of the selected renewable energy resources of the village.

#### 4.2.1.1 Wind Data Input

HOMER uses wind speed data to calculate the output of the wind turbines of the system and to determine the power sources that are required to meet the demand for electricity. The wind data can be imported directly into the software as hourly measurements or monthly averages for one year. HOMER generates synthetic hourly wind data from the monthly averages data when hourly wind speed measurements are not available using four parameters. Those are Weibull shape factor (k), autocorrelation factor, diurnal pattern strength and hour of peak wind speed.

The shape factor is a value of the long term distribution of wind speed. The default value of k is 2 and most wind regimes can be represented fairly and accurately at this value. The autocorrelation factor is a measure of the randomness of the wind. The value autocorrelation factor for places with complex topography ranges between 0.7 and 0.8. The value of autocorrelation factor for uniform topography sites range between 0.9 and 0.97. Diurnal strength is a measure of how strongly the wind speed depends on the tome of the day. Hour of peak wind speed is the time of a day that to be windiest. The overall input data of wind resource is shown in the figure 4.3 below.

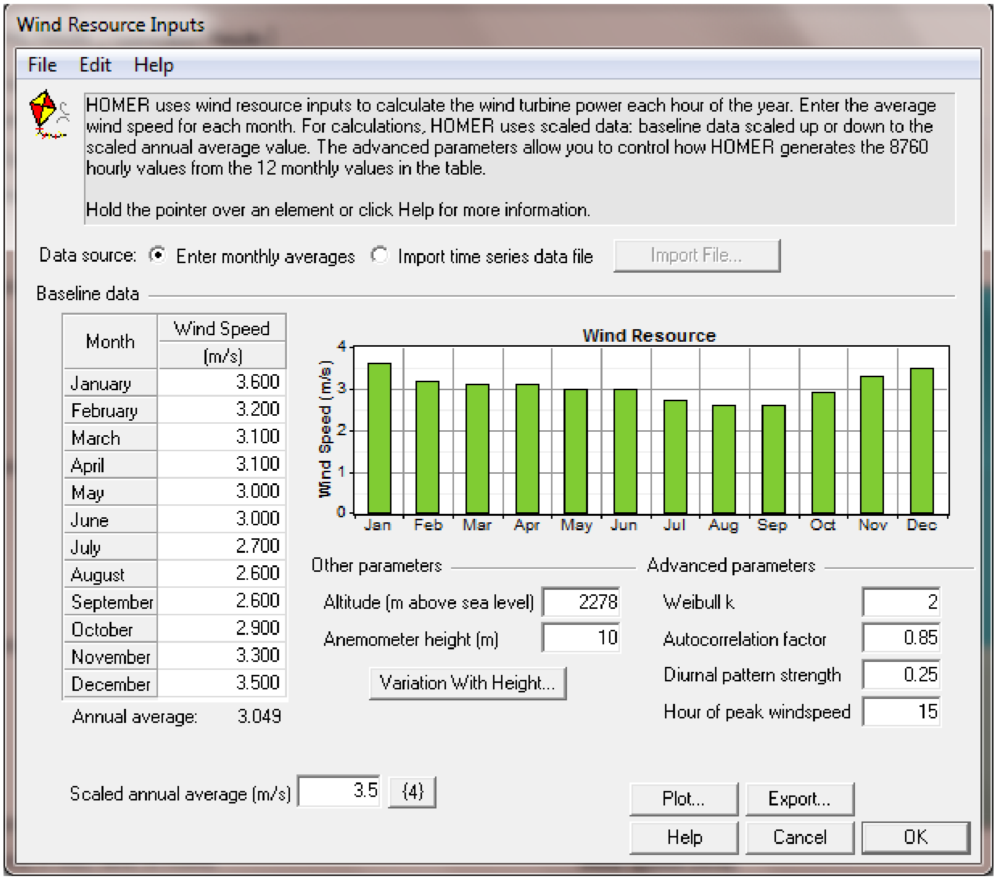


Figure 4-3 Wind energy resource of the site [NASA]

The monthly average wind resource data from an average of ten years was taken from the NASA. Figure 4.3 shows the annual average wind speed for the location is 3.1 m/sec with the anemometer height of 10 meters.

#### 4.2.1.2 Micro Hydro Data Input

Figure 4.4 illustrates the monthly average flows in the Ketar River. The scale annual average flow is assumed as 2100 liter/sec. The hydro resource graph in the figure below shows that, the flow in the river falls from September to January and rapidly increases up to 56,981.0 l/sec in August because of the heavy rainy season in the area. Similarly power generation potential of the hydro source does not remain constant throughout the year.

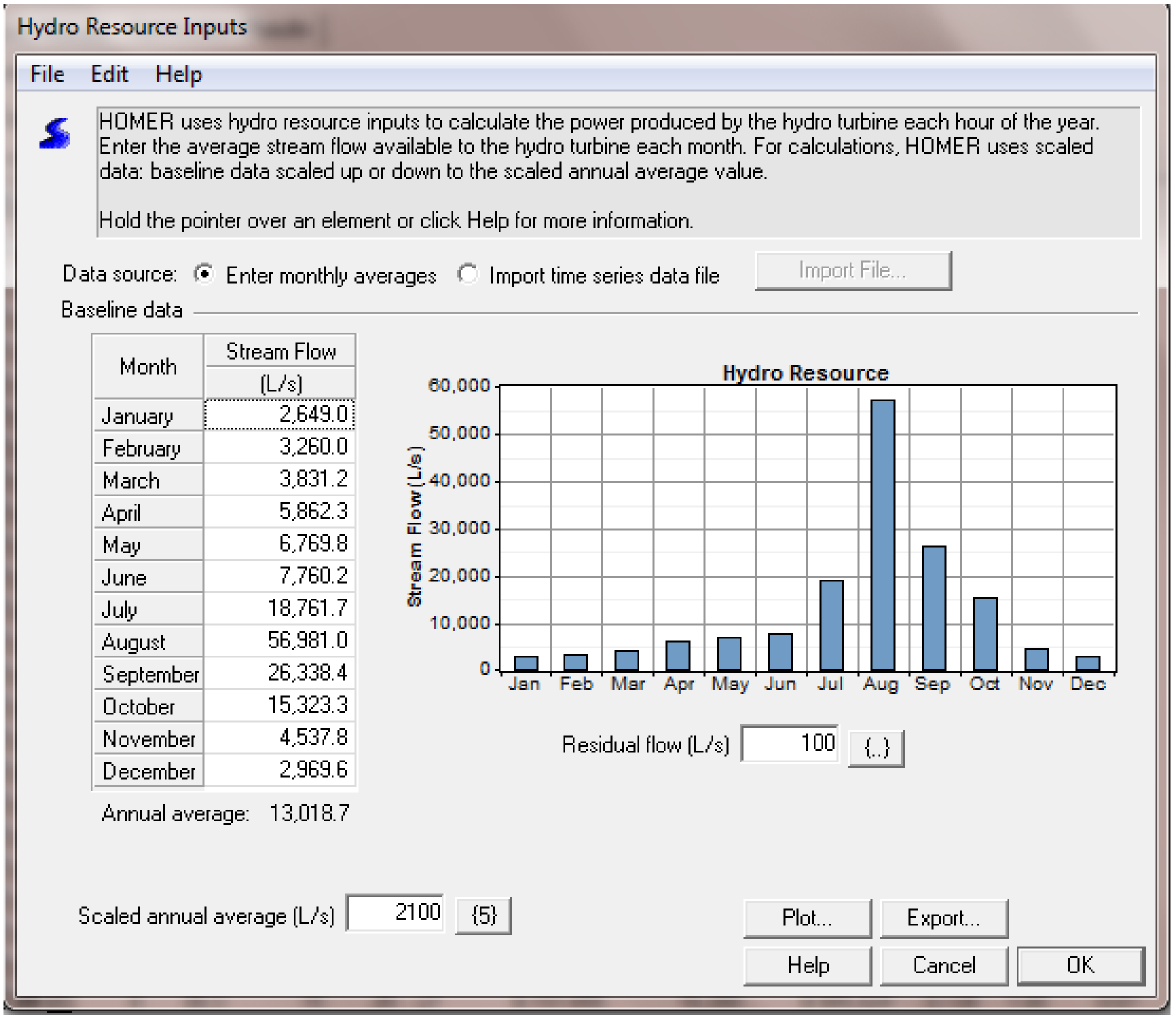


Figure 4-4 Micro hydro energy resource of the site [Ministry of Water and Energy]

#### 4.2.1.3 Demand Load Input

The Load required for any power generation system is one of the most vital parameters for its design. Knowing the magnitude of the energy demand of a particular site allows setting a lower limit for the project and estimating a preliminary upper boundary. Hence the electrical load should be introduced first to the software in order to select the necessary equipment to meet the demand load. The HOMER software requires input of hourly load data of one year or 8760 hours data. HOMER is capable to decide whether the equipment is sufficient to meet the load or not. Load data for this study is estimated in section 3.2. The hourly load demand is shown in figure 4.5

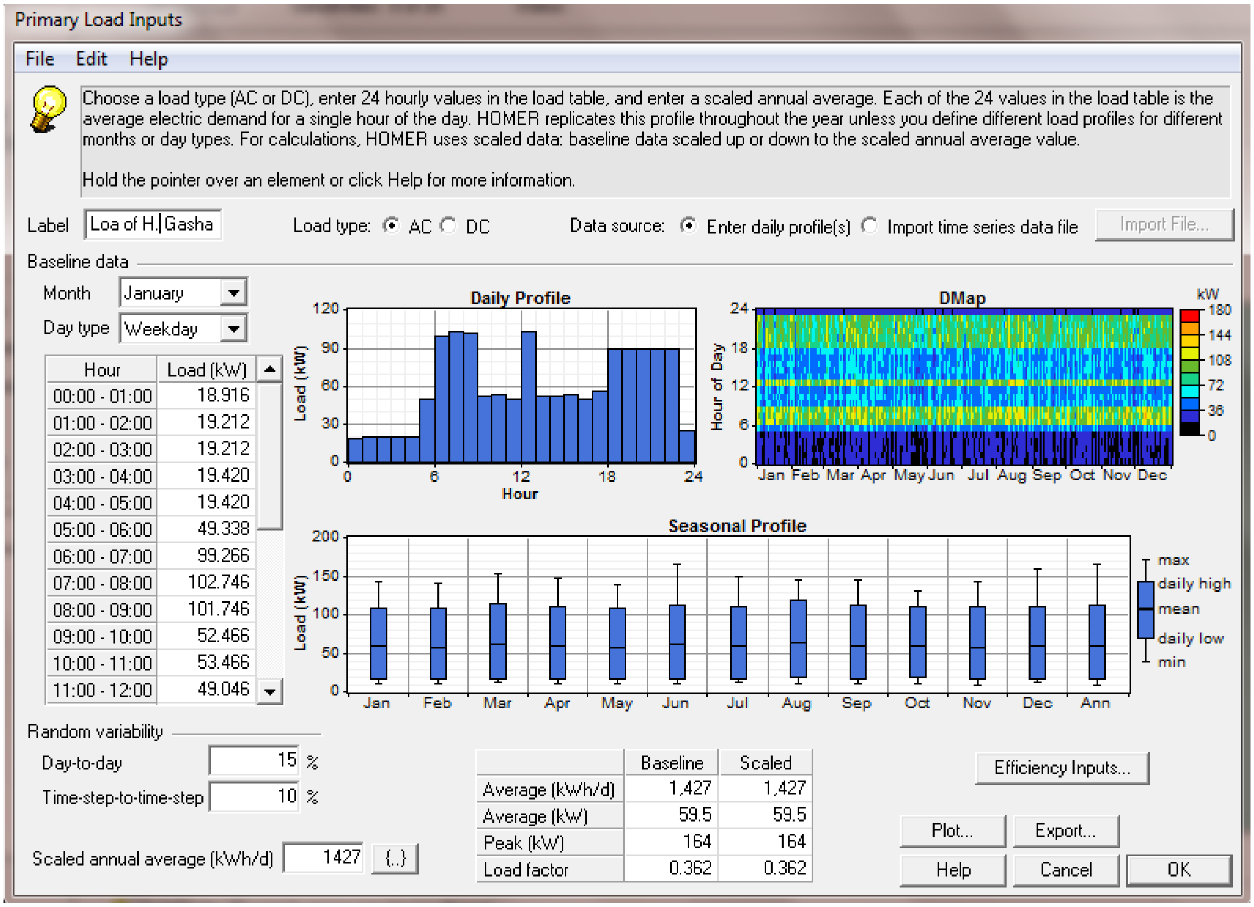


Figure 4-5 Hourly load of HOMER Input

### 4.2.2 Basic Components of the Hybrid System Designed for the Site

In this section the models of each components of the hybrid system are explained and the physical and economic properties of the system are discussed briefly. A component is any part of a hybrid system that generates delivers, converts, or stores energy. The component inputs express technology options, component costs, and the sizes and numbers of each component that HOMER will use for the simulations. This section describes how to enter cost data for wind turbines, micro-hydro turbine batteries and converters. And the sizes, types or quantity of each component are determined after repeated simulation trials.

#### 4.2.2.1 HOMER Model and Component Setup of the Hybrid System

It is required to create a new model using HOMER first to enter with inputs such as the technology options available like wind, solar, hydro etc, component cost and resource availability for instant flow rate, head for hydro resources and wind speed. HOMER simulates different system configurations using these inputs, and generates results that can be viewed as a list of feasible configurations sorted by net present cost. The simulation result from the software can be obtained in tables or graphs forms.

The fundamental components of the hybrid system of the selected village are the hydro system, the wind plant and auxiliary components that are used for full function of the hybrid system. Auxiliary components are equipments such as batteries, converters and other accessories

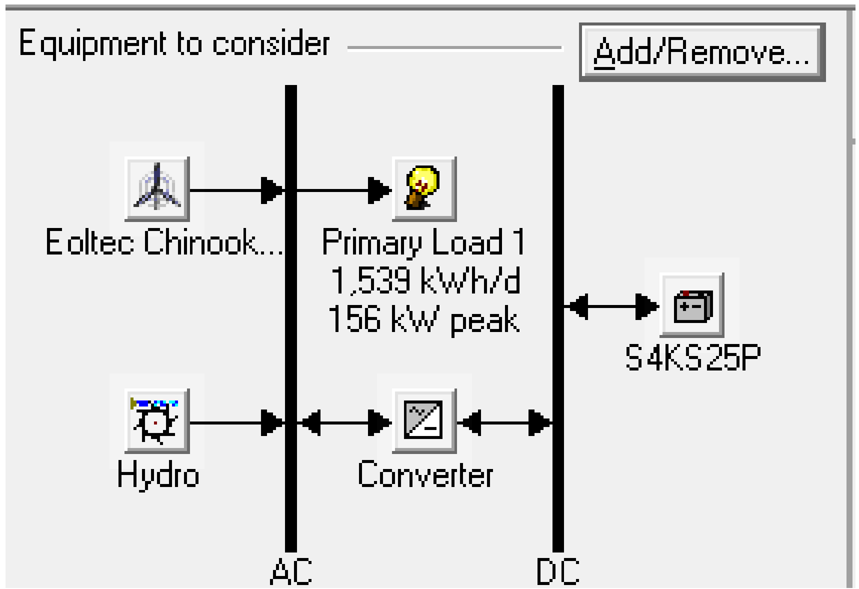


Figure 4-6 Hybrid System Configuration and selected renewable energy technologies.

The double headed arrow indicated in to the batteries and converters in the above figure have the following meanings. The converter change the excessive available power from AC to DC load to charge the batteries, after fully meeting the demand load of the system. When the output of the hybrid energy system is not enough to meet the load, the battery discharges the DC load to the system via the converter to power AC loads, as a source.

#### 4.2.2.2 Wind Turbine Input

HOMER models a wind turbine as a device that converts the kinetic energy of the wind into AC or DC electricity according to a particular power curve provided by the manufacturer of the turbine. The software calculates the power output of the wind turbine in each hour at standard air density, standard temperature and pressure conditions. HOMER considers the altitude when calculating the output of the wind turbine, since it affects air density; consecutively affects the wind turbine output [HOMER]. The wind class of the village is categorized under class one as mentioned in section 3.3.2. So small size wind turbines with low cut in wind speed are preferred for sites that have low wind power density. Hence, a 65 kW horizontal axis wind turbine is considered for this hybrid system. The amount of electricity generated by the wind turbine largely depends on the availability of wind and variations in the wind speed [43].

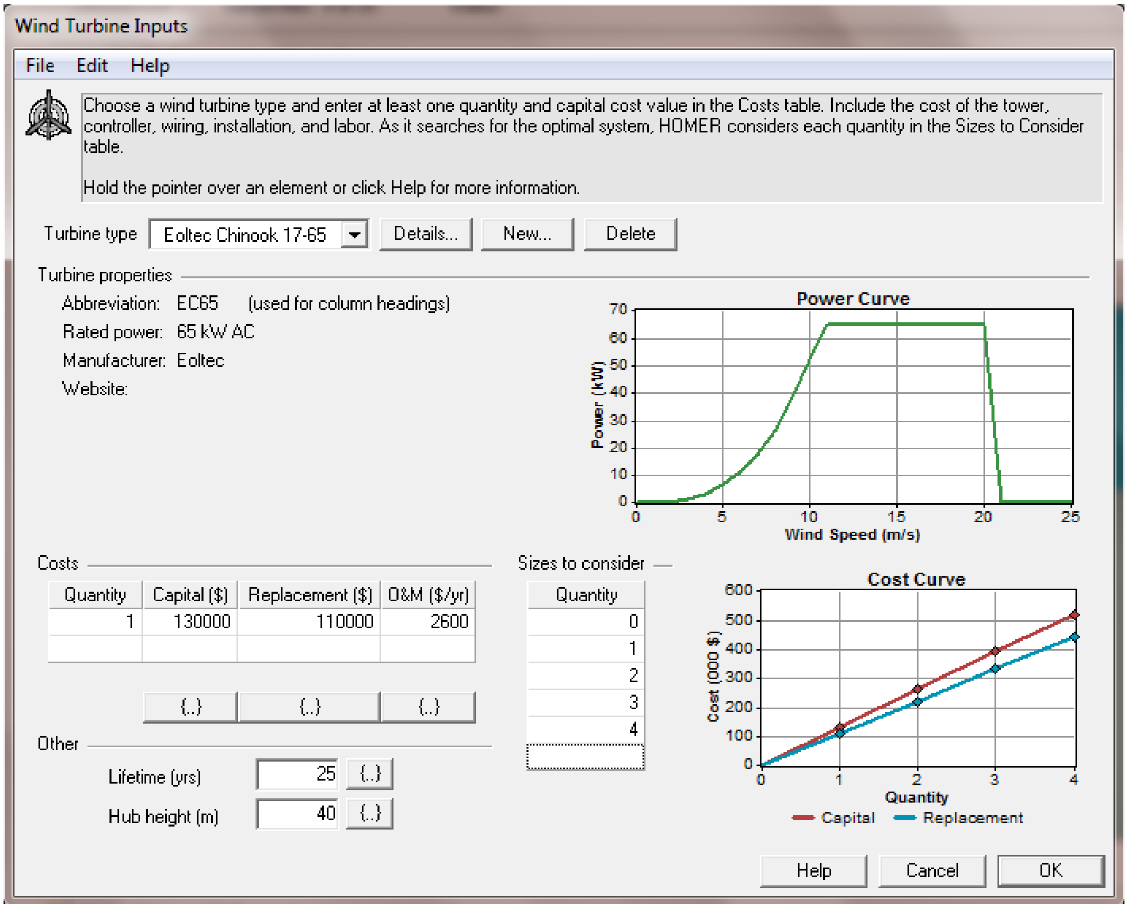


Figure 4-7 Wind turbine cost parameters and technical parameters

The selected wind turbine is indicated in figure 4.7 has a hub height of 40 meters and a lifetime of 25 years. The power and the cost curve for the wind turbine are also shown in the above figure. The initial capital costs of wind turbines vary significantly depending on the particular type being used and in different parts of the world. The initial cost (including installation civil works) of the small-scale wind turbines per kW is bigger than the large-scale wind turbines. The cost of one unit is considered as $130,000, while the replacement and the maintenance cost are taken to be $110,000 and $2600 per year respectively [10]. The replacement cost is the cost of replacing the wind turbine at the end of its lifetime [HOMER].

#### 4.2.2.3 Micro Hydro Power Input

The hydro turbine is modeled by the HOMER, as a mechanism that converts the power of falling water into ac or dc electricity at a constant efficiency. The hydro power in flowing water is proportional to the product of the stream flow and the head. The stream flow rate information necessary to the hydro turbine comes from the hydro resource data. HOMER calculates the net head from the input available head and the head loss that occurs in the intake pipe due to friction. [43]. Depending on the village load the micro hydro turbine is selected for a power output of 80.9 kW.

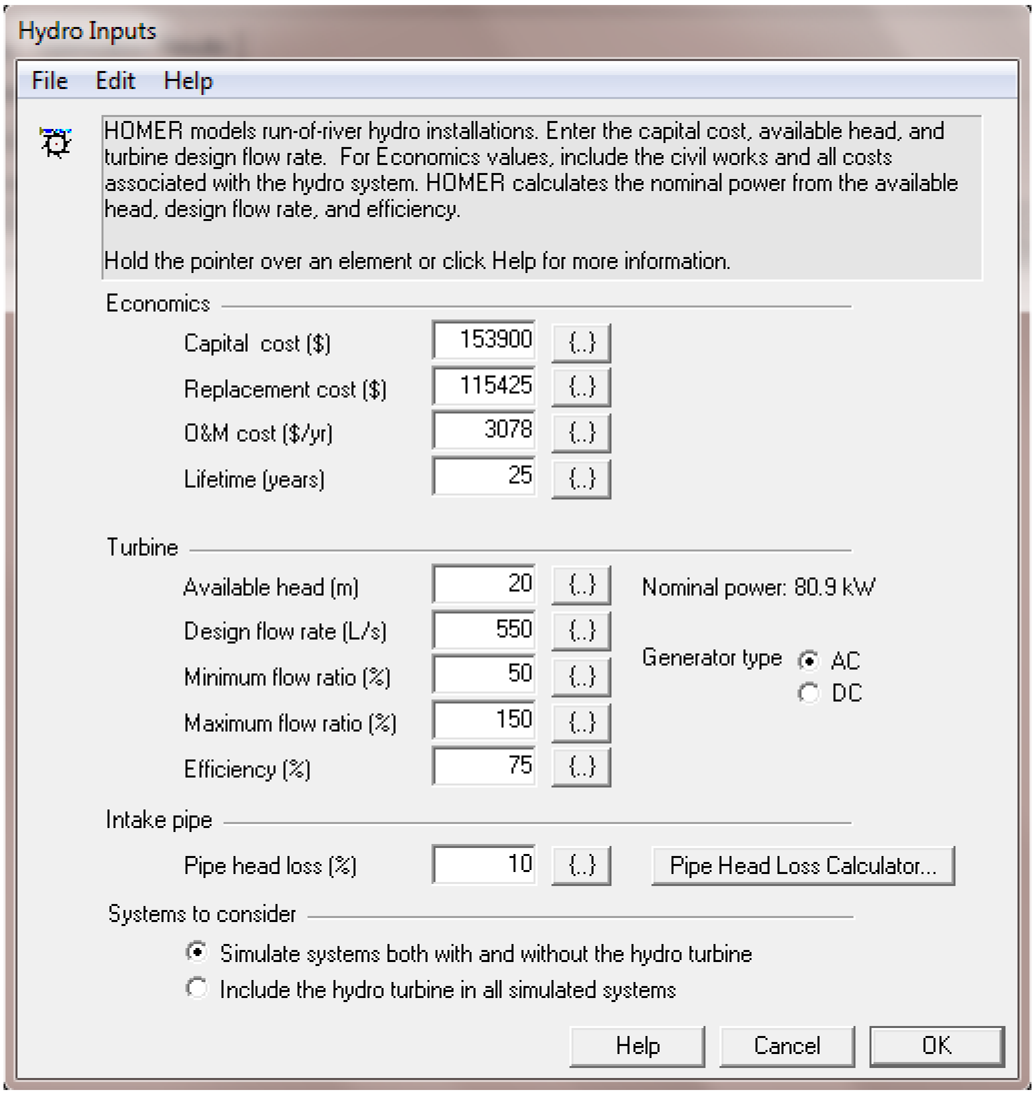


Figure 4-8 Micro Hydro technical and cost parameters

Figure 4.8 shows that the available head of the site is 20m and the design flow rate is selected to be 550litter/s. The designed flow rate is also selected after so many trial simulations. The turbine efficiency and the pipe head loss are 75% and 10% respectively. The out power of Micro Hydro Power generator is AC and the plant has a lifetime of 25 years. The capital cost, the replacement and O&M cost are taken as $ 153900, $ 115425 and $ 3078 respectively [6].

#### 4.2.2.4 Battery Input

Hybrid system can be reduced component over- sizing by storing the excess energy available at one time for usage during shortage time. There are different types of storage mechanism such as batteries, pumped storage, hydrogen etc.

Rechargeable batteries are widely used for implementation of hybrid energy systems because of their cheapness and easy operation**.** Batteries are an important component in a hybrid system that are used to store or back up energy. Batteries are charged when the electricity produced in the system is greater than the load and discharged when the demand is higher than the power generated or during pick hours. Thus battery storage is sized for meeting the variation in power between the renewable sources and the electrical load [10]. The Surrette 4KS25P battery was chosen for this study because of its good depth of discharge.

The main parameters of selecting batteries are maximum throughput and minimum state of charge. Maximum throughput is measured by the output of the battery (in ampere-hour) that can be delivered throughout its life time. Minimum state of charge is the measure of how low the battery can be discharged as a percentage of its full capacity without losing its performance. The above figure shows the input data for the battery used in this project. The capital and replacement cost of one battery is $14970 and O&M cost is assumed to be $299 per year [10].

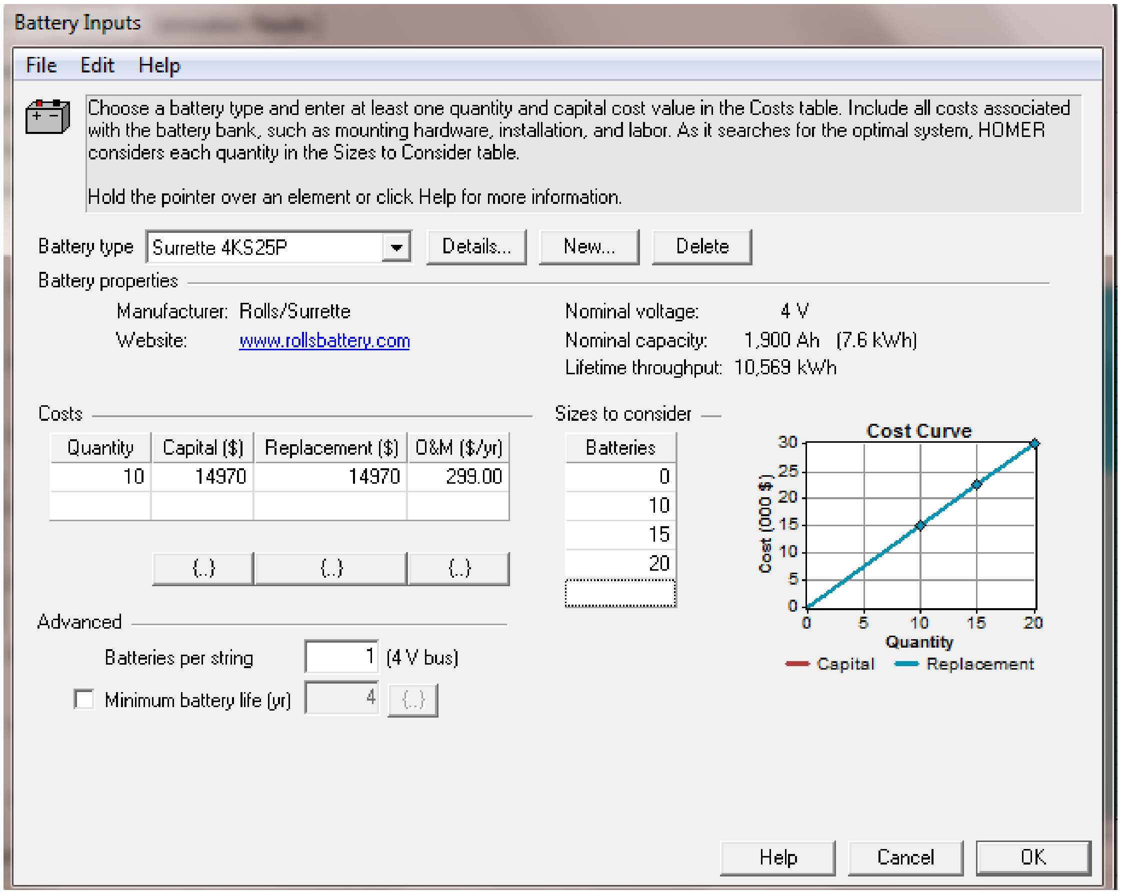


Figure 4-9 Battery cost input

### 4.2.2.5 Converter Input

A converter is an auxiliary power conditioning component that converts electric power from DC to AC in a process called inversion, and/or from AC to DC in a process called rectification. The decision variable of converter is the inverter and rectifier capacity, which refers the maximum amount of ac power and dc power that the device can produce by inverting dc power and by rectifying ac power respectively [43].

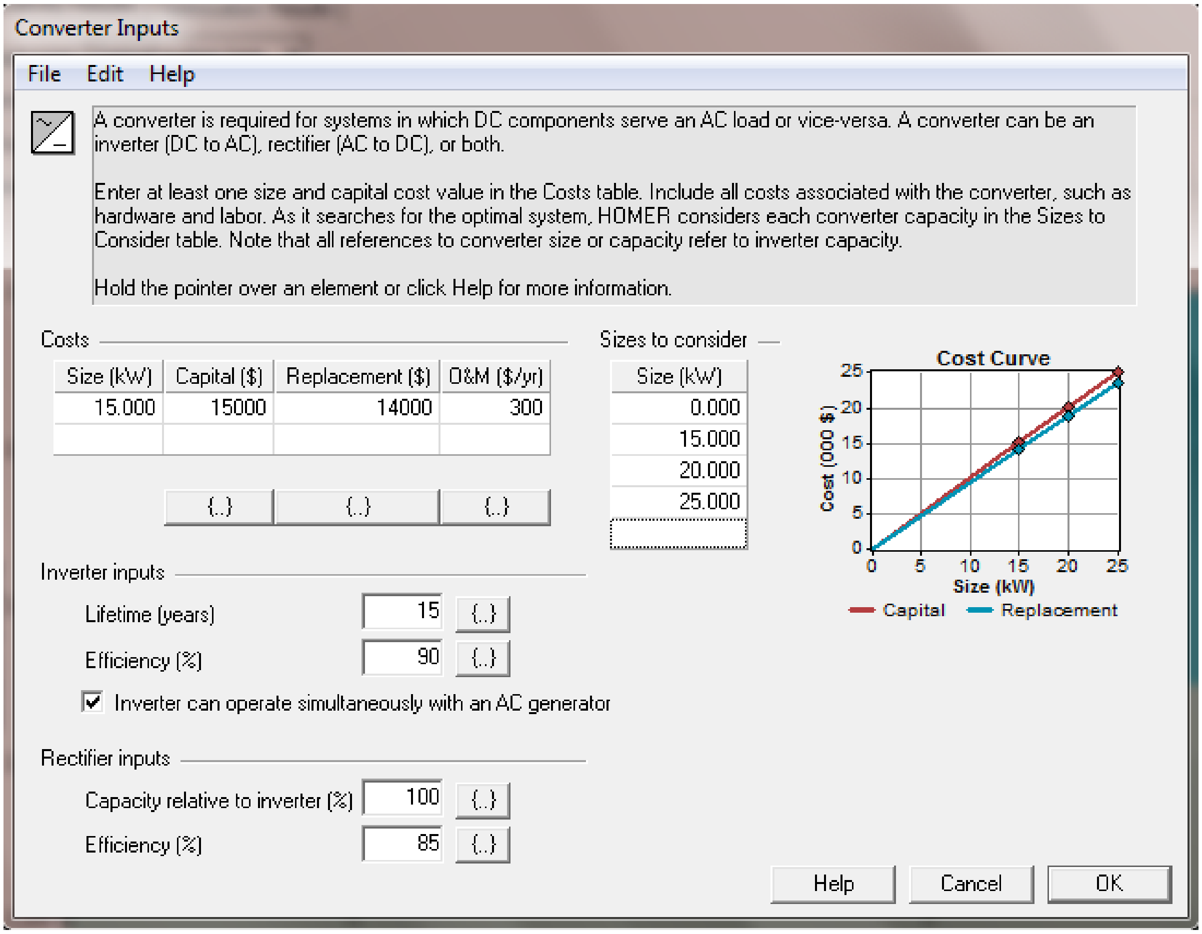


Figure 4-10 Converter cost Input

### 4.2.3 Other Inputs

#### 4.2.3.1 Economics Modeling Input

Since HOMER is subjected to select the minimum total net present cost (NPC) and to find the optimal system configuration economics input play a crucial role in the simulation. The project's lifetime is considered to be 25 years with an annual interest rate of 10%.

#### 4.2.3.2 Grid Extension Input

Breakeven grid extension distance ($S_{grid}$), the distance from the grid which makes the net present cost of extending the grid equal to the net present cost of the stand-alone system and HOMER calculates breakeven grid extension distance ($S_{grid}$) using the equation below [HOMER].

$$S_{grid} = \frac{C_{NPC} * CRF(i, R_{proj}) - C_{power} * L_{tot}}{C_{cap} * CRF(i, R_{proj}) + C_{om}} \quad (4.1)$$

Where, $C_{NPC}$ is total net present cost of the stand-alone power system ($), CRF is capital recovery factor,$R_{proj}$ is project life [yr], $L_{tot}$ is total primary and deferrable load (KWh/year), $C_{power}$ cost of power from the grid [$/kWh], $C_{cap}$ capital cost of grid extension [$/km], $C_{om}$ O&M cost of grid extension ($/yr/km) and i, is the interest rate(%).

To compare the standalone hybrid system with grid extension the grid extension inputs are necessary. And the grid is used as standard bench mark by HOMER, to be compared with the technical and cost parameters of the off-grid hybrid renewable energy technologies system. Thus the inputs of grid extension are taken in the analysis to see whether a grid extension is viable or not. The capital cost of grid extension per kilometer of the project is $12,500 [5]. Operation and maintenance of system is 2% the capital cost which is $250 where as the grid power price $/kWh is 0.06 [EEPCo].

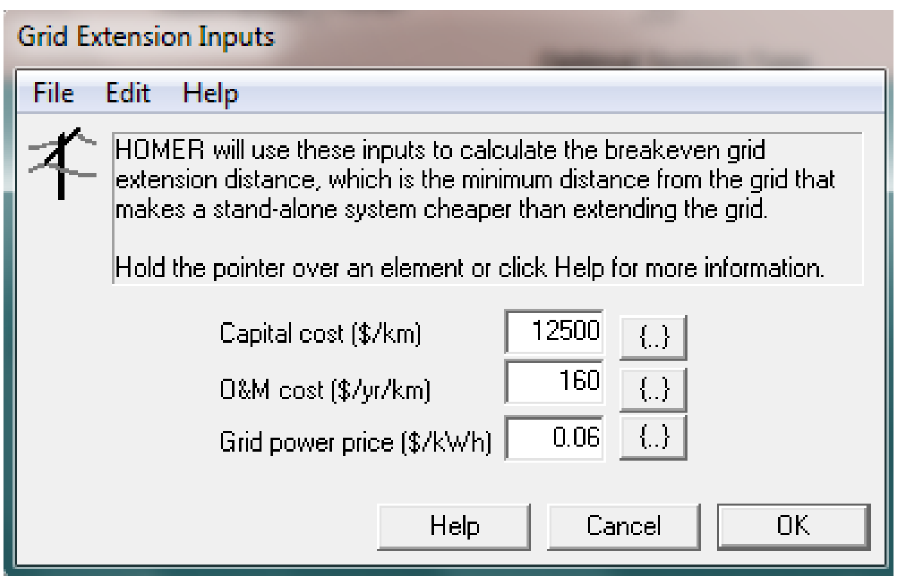


Figure 4-11 Grid extension input

# CHAPTER FIVE

## 5 Results and Analysis

### 5.1 Introduction

In this chapter, the results of the modeling and simulation of a wind-micro hydro hybrid and a standalone micro hydro power generation system for Hamsa Gasha village is presented. The concept, formulas and tables discussed in previous chapters are used as input for this chapter to evaluate hybrid renewable energy system. In the economic analysis, the life time period of the both systems is assumed to be 25 years with maximum annual capacity shortage of 8%.

In this chapter, the simulation results of the wind-micro hydro hybrid and a standalone micro hydro power generation system of the village are discussed in detail. Based on the simulation results, comparison of the standalone hybrid system versus the grid connected system is also carried out.

### 5.2 Simulation Results of Wind/Micro Hybrid System

Based on the input data that are discussed in the previous sections, HOMER software simulations were performed repeatedly by varying parameters that have a controlling effect over the output for each of the 8,760 hours of a year to find optimum solutions. The simulation software provides the results in terms of optimal systems and the sensitivity analysis. The output of the simulation is a list of feasible combinations of hydraulic turbine, wind turbine, battery and converter. Options for considering no wind turbine, battery and converter are used. The optimization and sensitivity results are presented in the following paragraphs.

Table 5-1 Summarized components inputs

| | Micro Hydro Turbine | Wind Turbine | Battery | Converter |
|---|---|---|---|---|
| Size(kW) | 80.9 | 65 | 1900Ah | 1 |
| Capital Cost($) | 153,900 | 130,000 | 14,970 | 15,000 |
| Replacement Cost($) | 115,425 | 110,000 | 14,970 | 14,000 |
| O&M cost ($/year) | 3,078 | 2,600 | 299.00 | 300 |
| Considered quantities | ---------- | 0, 1, 2, 3, 4 | 0, 10, 15, 20 | -------- |

| | | | | |
|---|---|---|---|---|
| Considered size(kW) | 80.9 | -------- | ----------- | 0, 15, 20, 25 |

### 5.2.1 Optimization Results

In the optimization process, HOMER simulates every system configuration with all of the combinations of components as specified in their component input and displays the results in a table. The software performs hundreds or thousands of hourly simulations to ensure best possible matching of demand and supply and sorts the feasible combinations based on the total net present cost (NPC) since it is used as the main selection tool in this section. The approach taken in this simulation is to ensure the energy conversion system provides adequate power to meet the energy demand. The micro hydro and wind turbine energy sources in association with battery and converter were evaluated to determine the feasibility of the system. All possible hybrid system configurations are listed in ascending order of their total NPC in the figure 5.1 shown below. The optimization results are listed in table either in an overall or in a categorized form which represents feasible system configurations to full fill the system load and constraints. Only the most cost effective configurations of the hybrid system are displayed in categorized form. Whereas, the overall optimization table displays all feasible system configurations of the system ranked in their cost effectiveness.

The following simulated optimization results of the hybrid system are listed; size of each component, capital cost, replacement cost and operating and maintenance cost of each system and levelized cost of energy (COE). The system is also simulated in order to evaluate its operational characteristics, namely annual electrical energy production, excess electricity, renewable energy fraction, capacity shortage and unmet electric load. The optimization result that indicates the technical and economical details of all the configurations of the hybrid systems from the optimization process are shown in detail in figure 5.1. This system is considered at sensitivity variables of 3.5m/s wind speed and 2100liter/s stream flow rate as shown in figure. The highlighted combination is able to meet Hamsa Gasha's village load demands at the lowest possible total NPC since the system with the overall least cost of energy is listed first. As shown in the first line, the best possible combination of the renewable resources for the hybrid system is wind, micro hydro battery and converter at the selected sensitivity variables.

Calculate | Simulations: 320 of 320 | Sensitivities: 25 of 25 | Progress: | Status: Completed in 42 seconds.

Sensitivity Results | Optimization Results

Sensitivity variables

Wind Speed (m/s) 3.5 | Stream Flow (L/s) 2,100

Double click on a system below for simulation results. | Categorized | Overall

| EC65 | Hydro (kW) | S4KS25P | Conv. (kW) | Disp. Strgy | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. | Capacity Shortage |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 80.9 | 20 | 20 | CC | $ 593,840 | 13,614 | $ 767,874 | 0.112 | 1.00 | 0.08 |
| 3 | 80.9 | 20 | 20 | LF | $ 593,840 | 13,614 | $ 767,874 | 0.112 | 1.00 | 0.08 |
| 3 | 80.9 | 20 | 25 | CC | $ 598,840 | 13,838 | $ 775,737 | 0.113 | 1.00 | 0.08 |
| 3 | 80.9 | 20 | 25 | LF | $ 598,840 | 13,838 | $ 775,737 | 0.113 | 1.00 | 0.08 |
| 4 | 80.9 | 10 | 15 | CC | $ 703,870 | 15,070 | $ 896,515 | 0.131 | 1.00 | 0.08 |
| 4 | 80.9 | 10 | 15 | LF | $ 703,870 | 15,070 | $ 896,515 | 0.131 | 1.00 | 0.08 |
| 4 | 80.9 | 10 | 20 | CC | $ 708,870 | 15,294 | $ 904,378 | 0.132 | 1.00 | 0.08 |
| 4 | 80.9 | 10 | 20 | LF | $ 708,870 | 15,294 | $ 904,378 | 0.132 | 1.00 | 0.08 |
| 4 | 80.9 | 15 | 15 | CC | $ 711,355 | 15,530 | $ 909,881 | 0.132 | 1.00 | 0.08 |
| 4 | 80.9 | 15 | 15 | LF | $ 711,355 | 15,530 | $ 909,881 | 0.132 | 1.00 | 0.08 |
| 4 | 80.9 | 10 | 25 | CC | $ 713,870 | 15,518 | $ 912,242 | 0.133 | 1.00 | 0.08 |
| 4 | 80.9 | 10 | 25 | LF | $ 713,870 | 15,518 | $ 912,242 | 0.133 | 1.00 | 0.08 |
| 4 | 80.9 | 15 | 20 | CC | $ 716,355 | 15,754 | $ 917,744 | 0.133 | 1.00 | 0.07 |
| 4 | 80.9 | 15 | 20 | LF | $ 716,355 | 15,754 | $ 917,744 | 0.133 | 1.00 | 0.07 |
| 4 | 80.9 | 20 | 15 | CC | $ 718,840 | 15,990 | $ 923,247 | 0.134 | 1.00 | 0.07 |
| 4 | 80.9 | 20 | 15 | LF | $ 718,840 | 15,990 | $ 923,247 | 0.134 | 1.00 | 0.07 |
| 4 | 80.9 | 15 | 25 | CC | $ 721,355 | 15,978 | $ 925,607 | 0.135 | 1.00 | 0.07 |
| 4 | 80.9 | 15 | 25 | LF | $ 721,355 | 15,978 | $ 925,607 | 0.135 | 1.00 | 0.07 |
| 4 | 80.9 | 20 | 20 | CC | $ 723,840 | 16,214 | $ 931,110 | 0.135 | 1.00 | 0.07 |
| 4 | 80.9 | 20 | 20 | LF | $ 723,840 | 16,214 | $ 931,110 | 0.135 | 1.00 | 0.07 |
| 4 | 80.9 | 20 | 25 | CC | $ 728,840 | 16,438 | $ 938,973 | 0.136 | 1.00 | 0.07 |
| 4 | 80.9 | 20 | 25 | LF | $ 728,840 | 16,438 | $ 938,973 | 0.136 | 1.00 | 0.07 |

Figure 5-1: Overall optimization results sorted by total NPC of Hamsa Gasha village.

Based on the best possible combination of the renewable resources, the monthly average energy production of each component of the hybrid system is shown in the figure 5.2 below. Majority of the energy demand of the village will be covered from micro hydro system. And the wind turbine contributes only 16% to the energy requirement of the village. The hybrid system produces 41.9% excess energy and this can be used to electrify another nearby villages.

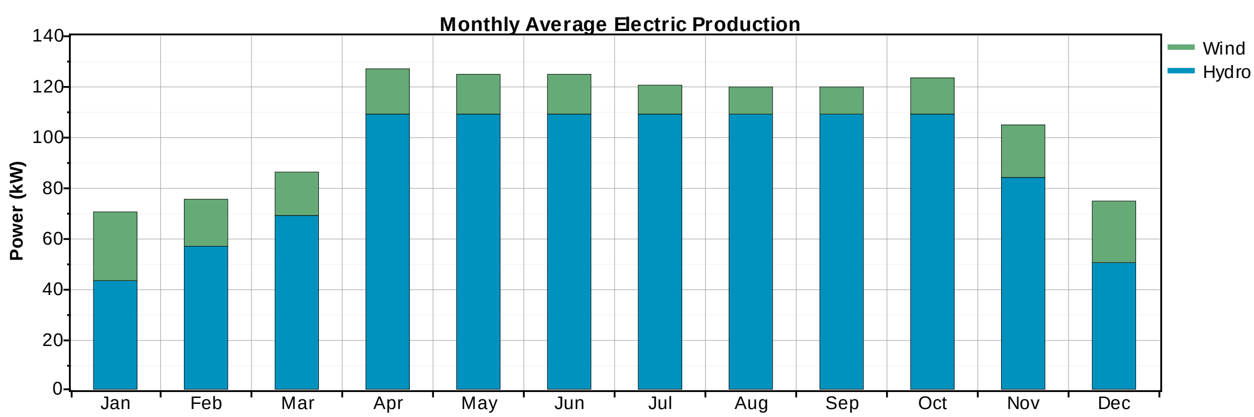


Figure 5-2 Monthly electrical energy production of the hybrid system

According to the optimization results, the most favorable combination of renewable energy technology components are a 80.9kW micro hydro, 3 Eoltec Chinook17-65 wind turbine, 20 Surrette 4KS25P Batteries and 20kW converter. The total NPC and the initial capital cost for such a hybrid system are $767,874 and $ 593,840 respectively. The initial capital cost of the hybrid system is the total installed costs of those components at the beginning of the project. The levelized cost of energy (COE) of the hybrid system is estimated to be $0.112/kWh (ETB 2.11/kWh) which is larger than the current electricity tariff of Ethiopia that is $0.06/kWh (ETB 1.13/kWh). The economic performance of the winning system for Hamsa Gasha village is summarized in table 5.2, table 5.3 and Figure 5.3.

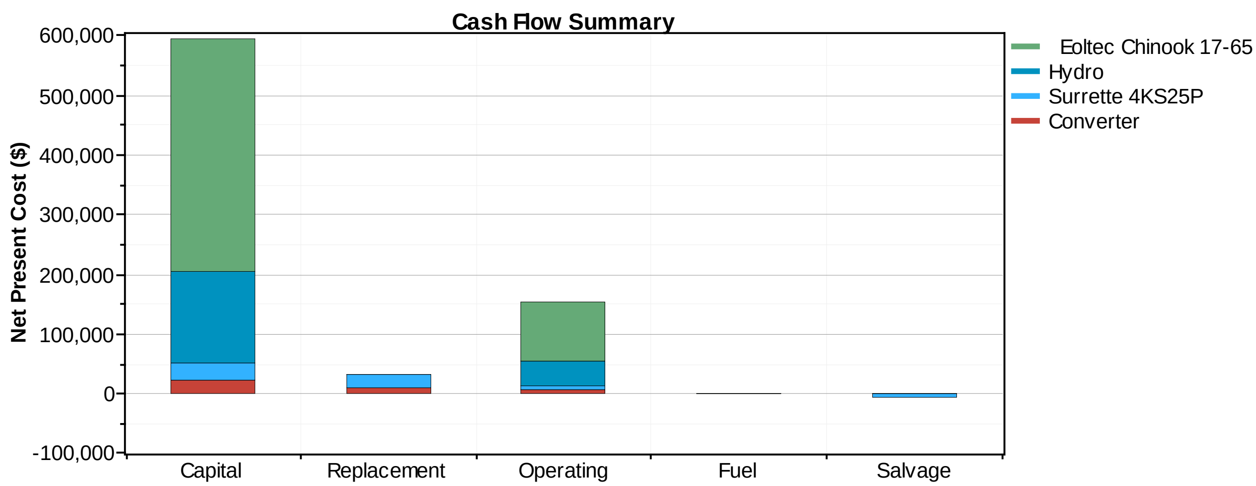


Figure 5-3 Cash flow summary of the hybrid system

The batteries and the converter have a low impact on the capital and O&M costs of the hybrid system as indicated in the above cash flow summary graph. The annualized cost of the proposed hybrid system components is listed in table 5.3.

Table 5-2 Net present costs(ETB)

| Component | Capital | Replacement | O&M | Fuel | Salvage | Total |
|---|---|---|---|---|---|---|
| Eoltec Chinook 17-65 | 7,348,848 | 0 | 1,878,855 | 0 | 0 | 9,227,703 |
| Hydro | 2,899,968 | 0 | 741,423 | 0 | 0 | 3,641,392 |
| Surrette 4KS25P | 564,165.4 | 419,713 | 144,037 | 0 | -12,0502 | 1,007,433 |
| Converter | 376,864 | 146,770 | 96,345 | 0 | -27,322 | 592,675 |
| System | 11,189846 | 566,483 | 2,860,662 | 0 | -147,825 | 14,469,203 |

Table 5-3 Annualized costs(ETB/year)

| Component | Capital | Replacement | O&M | Salvage | Total |
|---|---|---|---|---|---|
| Eoltec Chinook 17-65 | 574868 | 0 | 146977 | 0 | 721845 |
| Hydro turbine | 226853 | 0 | 57999 | 0 | 284853 |
| Surrette 4KS25P | 44131 | 32825 | 11268 | -9422 | 78802 |
| Converter | 29490 | 11476 | 7537 | -2129 | 46354 |
| System | 875342 | 44300 | 223782 | -11551 | 1131854 |

Note: - The changing rate of one USD is 18.8432 Ethiopian Birr (ETB) on April 24, 2013 [Commercial Bank of Ethiopia]

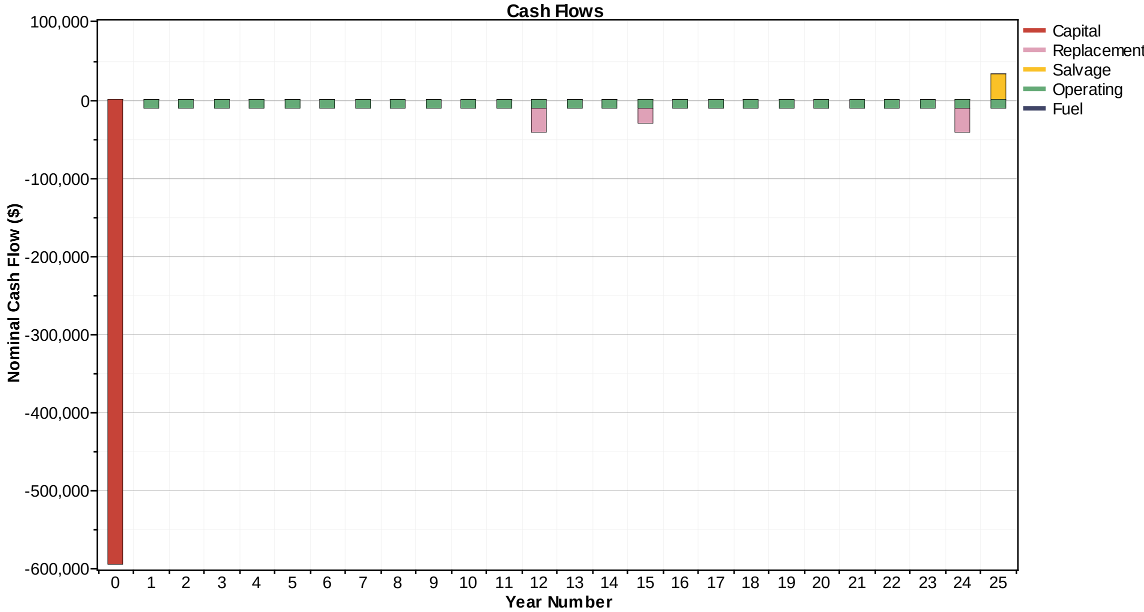


Figure 5-4 Yearly cash flow of the system

Figure 5.4 displays the yearly cash flow throughout the system's lifetime. Replacements for changing batteries and converters are taken place mainly in the 12$^{th}$, 15$^{th}$ and 24$^{th}$ year of the system.

### 5.2.2 Sensitivity Results

The sensitivity analysis answers the question what if a dynamic change exists on the input variables due to various reasons, such as increasing or decreasing load demand as well as changes regarding the resources, for example wind speed variations, fluctuations in the river's water flow rate or the energy component prices. To select the best suited combination for the hybrid system to serve the load demand wind speed and stream flow rate sensitive variables are considered here.  A range of wind speed from 3.5 to 6m/s and a river's flow rate from 2100 to 3000 liter/s are used as sensitivity parameters. The software simulates all the systems in their respective search space for each of the sensitivity values. Taking into account uncertainty parameters, sensitivity analysis eliminates all infeasible combinations and ranks the feasible combinations results in descending order of NPC. Where, a feasible system is the one that meets the required load at an affordable price. HOMER displays the sensitivity analysis both in tabular and graphical form.

The sensitivity analysis explains how the variations in average annual wind speed and stream flow rate of the river affect the optimal design of the system. The various sensitive variables are considered to let us see how the results are affected when one or each value of those variables is changed. The detail sensitivity result of the hybrid system is indicted graphical form in Figure 5.5. The figure shows how the system configuration changes due to changes in the sensitive variables, the average wind speed and stream flow rate. As shown in the graph below the optimal system design depends both on the annual average wind speed and on the river flow rate.

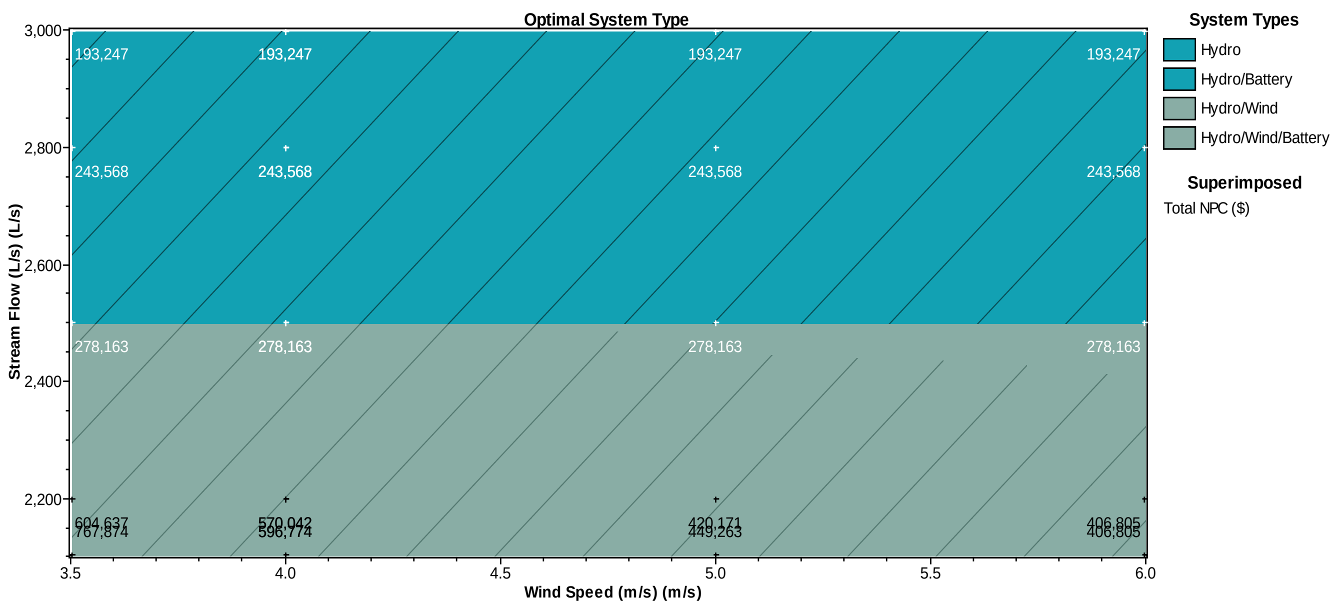


Figure 5-5 Sensitivity result graph

Based on the sensitivity analysis graph indicated above the total net present cost (NPC) of the hybrid system varies inversely with annual average wind speed and stream flow rate. The system has the highest NPC at 3.5 m/s annual average wind speed and 2100liter/sec. stream flow rate. Whereas, the smallest NPC is found at 6m/s annual average wind speed and stream flow rate of 3000liter/sec. Generally, the levelized cost of energy (COE) micro hydro and wind hybrid systems become more favourable when the wind speed and flow rate are increasing as shown in Figure 5.5. At the highest NPC the levelized COE of the system is US$0.112/kWh and levelized COE is found to be US$0.028/kWh at the lowest NPC.

In addition, Figure 5.5 explains that the total net present cost of system configurations decreases rapidly when the flow rate tend to increase even keeping the wind speed constant. On the other hand, keeping the stream flow rate is constant and raising the wind speed the total net present cost minimizes slowly. Consequently, micro hydro power system is the cheapest technology compared to other renewable energy technology systems.

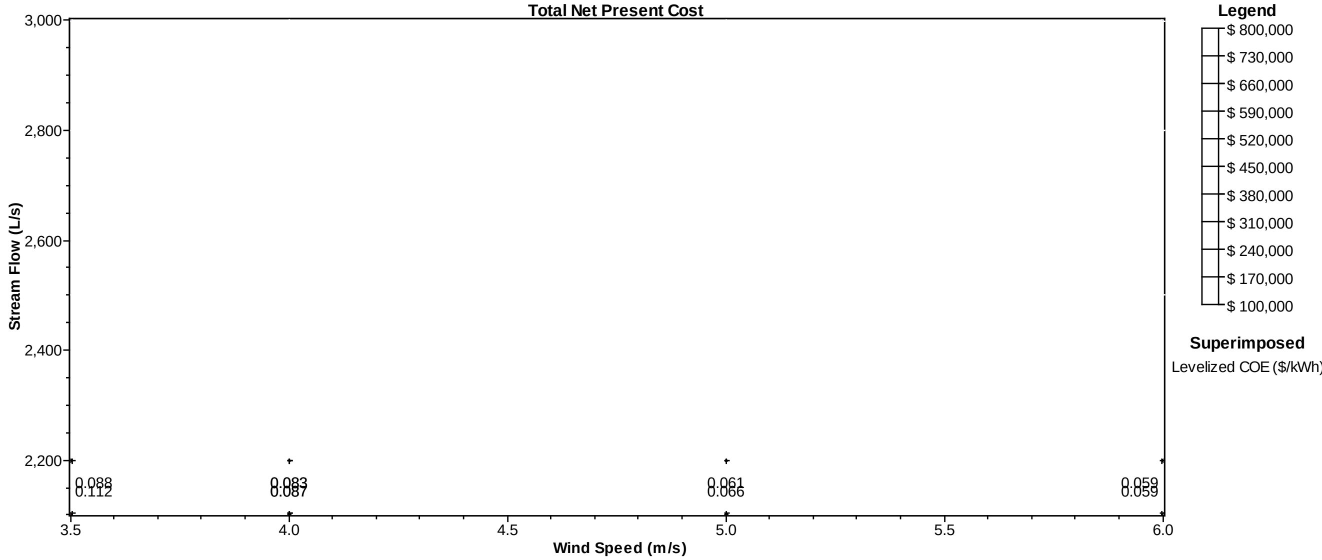


Figure 5-6 Surface plot of total NPC

Figure 5.6 demonstrates the surface plot for the total NPC with levelized COE superimposed. The wind speed variation is represented on the x-axis and stream flow rate on the y-axis. It can be observed that as stream flow rate increases, the power output from micro hydro increases and hence there is a reduction in total NPC. As the total NPC decrease, likewise the system's COE decreases. This shows that with a change in sensitivity variables the configurations of the system also changes.

### 5.2.3 Comparison of the Grid Extension with Standalone Hybrid Off Grid System

Breakeven distance for grid extension is distance from the grid which makes the net present cost of extending the grid equal to the net present cost of the stand-alone system. Depending on the values of sensibility variables the breakeven distance varies from negative value of 16.3 km to positive 23.2 km. Figure 5.7 below is a sensitivity graph superimposed with breakeven grid extension and it clearly shows the breakeven distance tend to be negative when the average wind speed and stream flow rate are increasing. And the breakeven grid extension distance lift up to positive value when average wind speed and stream flow rate are declining.

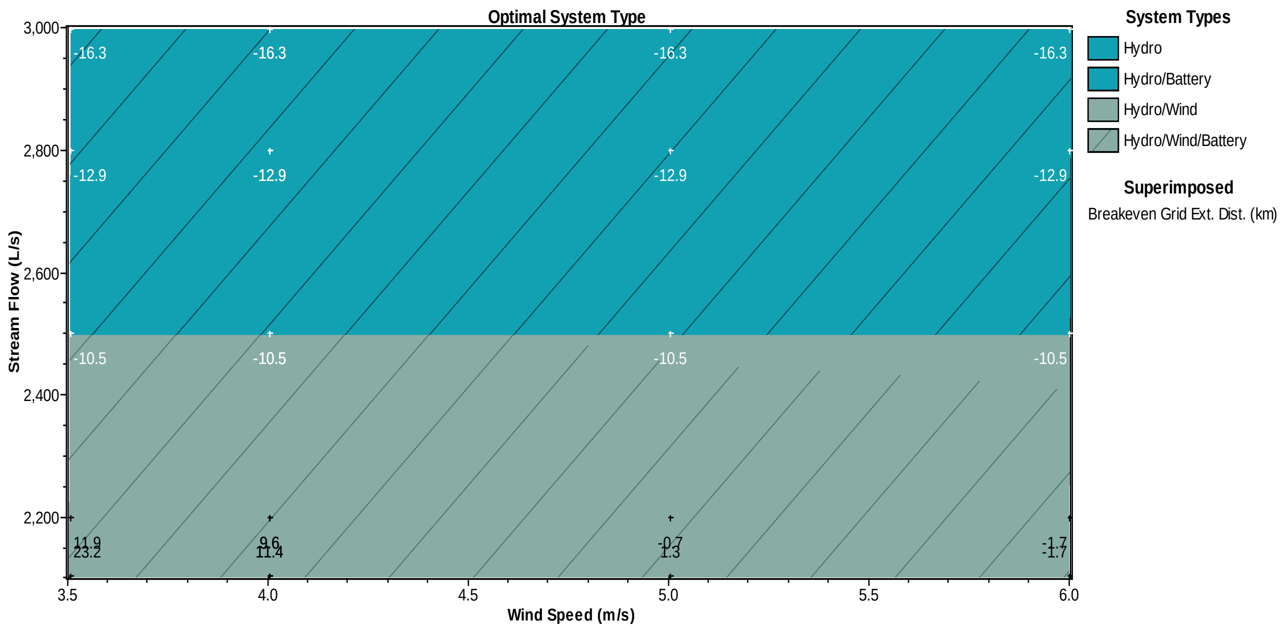


Figure 5-7 Sensitivity result superimposed with breakeven extension distance graph

If the sensitivity variables values of average wind speed and steam flow rate are 3.5m/s and 2100liter/sec respectively, the breakeven distance or economical distance limit of the hybrid system is 23.2km as indicated in the graph below. Nearer to the grid, grid extension is most favorable option. On the other hand, if the village is farther away from the grid, the stand-alone system is best option.

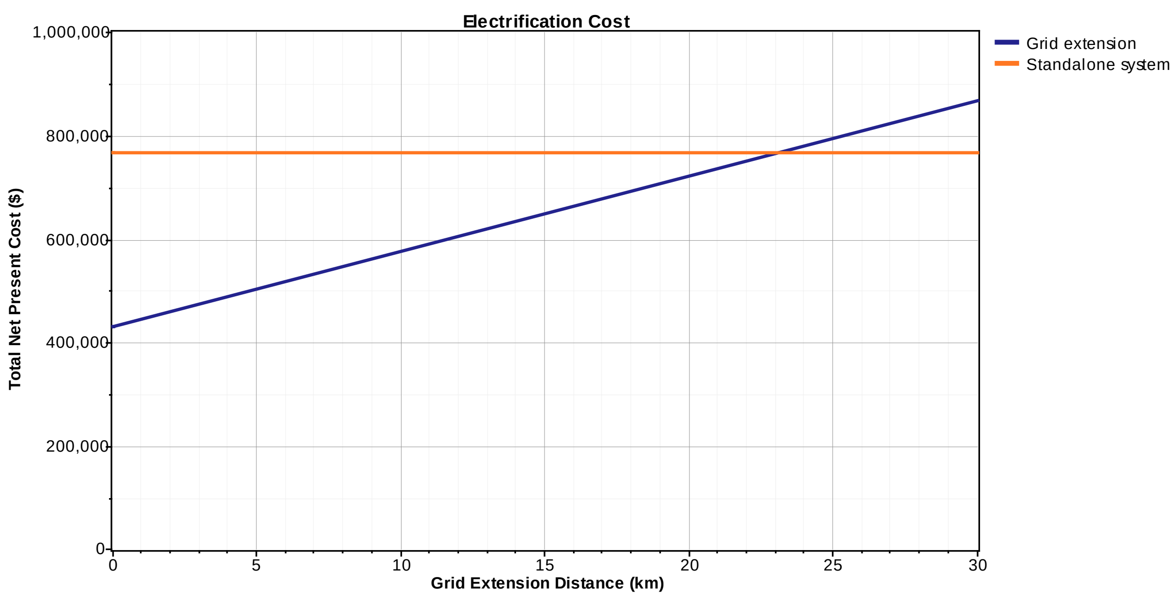


Figure 5-8 Comparison of grid extension with the standalone hybrid system

## 5.3 Simulation Results of a Standalone Micro Hydro System

From the Simulation results of wind/micro hydro hybrid system, the energy contribution of the wind system is negligible as compared to the micro hydro system. In contrast, the net present cost of the wind turbines is more than that of micro hydro turbine. This is because of the poor wind and high potential hydro energy sources of that particular site. Hence, a standalone micro hydro power generation system is favorable for the selected village.

The standalone micro hydro power system is simulated using a design flow rate of 0.67$m^3$/s and same gross head of that of wind/micro hydro hybrid system. Rated capacity of the standalone micro hydro generation system is 98.6kW. The simulation result shows the annual energy production of this system is 936,171kWh. The annual average energy requirement of the village is 547.2MWh (547,200kWh) as estimated in section 3.2. That means that the river can supply the local people safely and reliably without any requirement of supplementary sources. And excess electricity generating capacity of the micro hydro system is 415,774kWh/yr or 44.4%. This can help to expand the micro hydropower electric generation system of Hamsa Gasha village to other nearby villages.

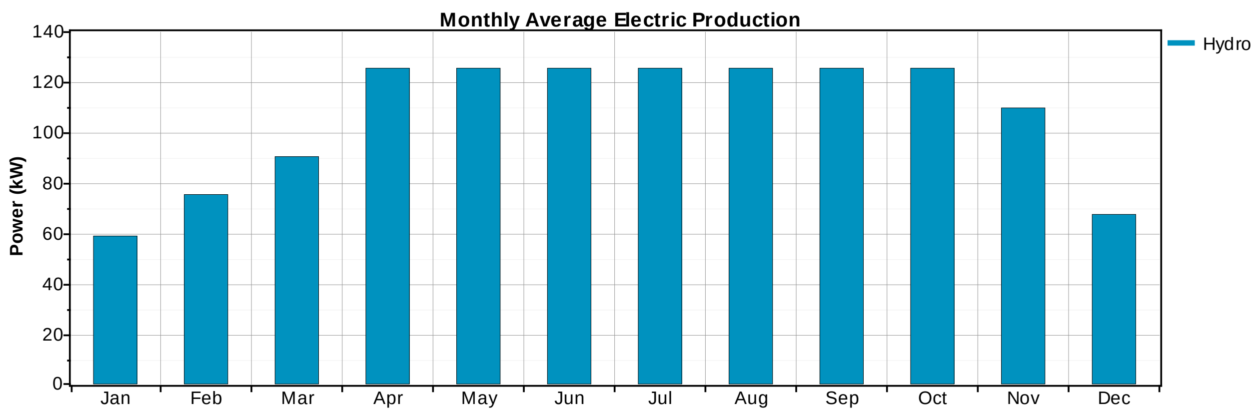


Figure 5-9 Monthly electrical energy production of the standalone micro hydro system

According to the optimization results of the standalone micro hydro system, the total NPC and the initial capital cost are $ 235,522 (ETB 4,437,988) and $ 187,572 (ETB 3,534,457) respectively that is much less than the hybrid system. Similarly, the levelized cost of energy (COE) of the micro hydro system is $0.035/kWh (ETB 0.66/kWh).

# CHAPTER SIX

## 6 Conclusions and Recommendation

### 6.1 Conclusions

The aim of this study is to model and simulate a micro hydro-wind hybrid power generation system for rural areas of Ethiopia. A hybrid system can be cost-competitive to supply energy for remote villages because of the high costs for a grid extension to be extended over a considerable distance and transmission and distribution losses associated with the grid. Providing electricity for rural areas helps to improve the life of the society. Hence a model community of 660 households with one primary school, two churches, one Mosque, and one health center is selected to achieve the plan of this study.

To accomplish the aim the study firstly the micro hydro and wind energy resources of the selected village has been assessed. In determining the wind energy potential of the sites, the study is based on 10 years average wind speed data obtained from the NASA. Whereas the micro hydro potential of the village estimated using the 18 years daily average of stream flow data of the river found from Ministry of Water and Energy and the head is surveyed from the site. And it is believed that this method of getting data is better option to researchers working on similar issues in developing countries, where properly recorded data is not available. Then the energy demand of the village is estimated based on the number of households. For the estimation of hourly electric load it is assumed that each household has a TV set, lighting, radio receiver, ‘Enjera’ stove. Moreover energy need by community for churches, mosque, health center, water pumps and flour mills is also calculated.

HOMER software was used as an aid for modeling and simulation of the hybrid system. HOMER has proved a valuable tool in this study especially because of its ability to simulate numerous components and load combinations. A standalone wind/micro hydro/battery hybrid system and only micro hydro system options are considered separately in order to electrify Hamsa Gasha Village. Based on the inputs of the software such as energy component, renewable energy resources that means, monthly average wind speed and micro hydro resources and others, the simulation results are obtained. These results acquired from the software give several alternatives of feasible combination systems with different levels of renewable resources penetration. The wind energy potential of the site may not be sufficient for a large independent wind farm, although it is found to be viable option if integrated into micro hydro power and battery. The results also confirmed the availability of huge utilizable hydro power at the site.

The initial capital cost and levelized cost of energy of the hybrid system depends on the selected sensitivity variables. When the average wind speed is 3.5m/s and stream flow rate is 2100 l/sec the optimum system comprises a hybrid micro hydro/wind/battery system. The initial capital cost and COE of this combination are US$ 593,840.00 and US$ 0.112/kWh respectively. Alternatively, if the average wind speed is 6 m/s and stream flow rate is 3,000 l/sec the best possible system consist of a hybrid micro hydro/wind system only. And the levelized COE and initial capital cost of this system at this condition are $ 153,900.00 and $ 0.028/kWh respectively. Moreover, the breakeven distance of the hybrid system varies between negative 16.3 km and positive 23.2km depending on the sensitivity variables
On the other hand the total NPC and the initial capital cost of the standalone micro hydro system is $ 235,522and $ 187,572 respectively that is much less than the hybrid system. Similarly, the levelized cost of energy (COE) of the micro hydro system is $0.035/kWh.

In fact the hybrid system has a relatively higher COE than the national tariff considering the life change of the poor in remote regions, acceleration of deforestation and clean energy development it may be another option to electrify the remote rural areas. The capital cost and levelized cost of energy (COE) of the micro hydro system is smaller than that of hybrid system. And the Author believes that implementation the standalone micro hydro system is economically feasible and pollution frees for this particular site because of its rich hydro power resources.

## 6.2 Recommendation and Further work

This thesis presents a micro hydro-wind hybrid energy system for remote villages of Ethiopia. And the work presented here could be used as a starting point for the development of the system. The followings are recommendations for further research and development relating to the remote rural electrification using hybrid renewable energy systems.
The author proposed that there may be better potential sites suitable for storage based and run of river type hydropower developments across Ketar River and accessing this individually may be

difficult. So a concerned body should be carried out a detailed study allocating more time and finance.

Furthermore, the study recommends collecting wind speed data at the actual site at different locations using a wind mast equal to the hub height of the selected wind turbine for at least one complete year.

Although the aim of this study to supply electrical energy for rural areas that are remote from the grid, it does not mean that it covers all villages around the country. Thus future researchers should make the rural people beneficial with renewable energy resource expanding this research work in to other sites.

Consequently, the major areas for further search should be:

- The accurate measurement of the renewable energy resources such as, wind speed and flow rate at the selected site.
- forecasting the energy demand of the village with respect to population and economic growth rate
- Integrating the standalone hybrid power systems with the national grid
- Detailed design of each component

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# Appendix A

Week days hourly load estimation of the village

Load Estimation of large house

| S.No | Appliance Type | Quantity | Power(W) | period of time(hr) | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 00--1 | 1--2 | 2--3 | 3--4 | 4--5 | 5--6 | 6--7 | 7--8 | 8--9 | 9--10 | 10--11 | 11--12 | 12--13 | 13--14 | 14--15 | 15--16 | 16--17 | 17--18 | 18--19 | 19--20 | 20--21 | 21--22 | 22--23 | 23--00 |
| | Domostic | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | Lighting | 3 | 11 | | | | | | | | | | | | | | | | | | | 33 | 33 | 33 | 33 | 33 | |
| 2 | Radio | 1 | 10 | | | | | | | 10 | 10 | 10 | | | | 10 | | | | | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 3 | TV | 1 | 70 | | | | | | | | | | | | | 70 | | | | | | 70 | 70 | 70 | 70 | 70 | |
| 4 | Cooking | 1 | 3000 | | | | | | 166.7 | 166.7 | 166.7 | 166.7 | 166.7 | 166.7 | 166.7 | 166.7 | 166.7 | 166.7 | 166.7 | 166.7 | 166.7 | | | | | | |
| 5 | Miscellaneous | | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| | no.l.house | 180 | | | | | | | | | | | | | | | | | | | | | | | | | |
| | sub total | | | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 35.41 | 37.21 | 37.206 | 37.206 | 35.406 | 35.406 | 35.406 | 49.81 | 35.41 | 35.406 | 35.41 | 35.406 | 37.206 | 25.74 | 25.74 | 25.74 | 25.74 | 25.74 | 7.2 |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Load Estimation of small houses | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| S.No | Appliance Type | Quantity | Power(W) | period of time(hr) | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | 00--1 | 1--2 | 2--3 | 3--4 | 4--5 | 5--6 | 6--7 | 7--8 | 8--9 | 9--10 | 10--11 | 11--12 | 12--13 | 13--14 | 14--15 | 15--16 | 16--17 | 17--18 | 18--19 | 19--20 | 20--21 | 21--22 | 22--23 | 23--00 |
| | Domostic | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | Lighting | 3 | 11 | | | | | | | | | | | | | | | | | | | 33 | 33 | 33 | 33 | 33 | |
| 2 | Radio | 1 | 8 | | | | | | | 10 | 10 | 10 | | | | 10 | | | | | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 3 | TV | 1 | 70 | | | | | | | | | | | | | 70 | | | | | | 70 | 70 | 70 | 70 | 70 | |
| 4 | Miscellaneous | | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| | no.l.house | 480 | | | | | | | | | | | | | | | | | | | | | | | | | |
| | sub total | | | 14.4 | 14.4 | 14.4 | 14.4 | 14.4 | 14.4 | 19.2 | 19.2 | 19.2 | 14.4 | 14.4 | 14.4 | 52.8 | 14.4 | 14.4 | 14.4 | 14.4 | 19.2 | 68.64 | 68.64 | 68.64 | 68.64 | 68.64 | 19.2 |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Public load | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| school | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | lighting | 36 | 11 | 44 | 44 | 44 | 44 | 44 | 44 | | | | | | | | | | | | 396 | 396 | 396 | 44 | 44 | 44 | 44 |
| 2 | office load | 1 | 200 | | | | | | | | | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | | | | | | | | |
| 3 | miscellaneous | 1 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| | sub total | | 0.261 | 0.094 | 0.094 | 0.094 | 0.094 | 0.094 | 0.094 | 0.05 | 0.05 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.05 | 0.446 | 0.446 | 0.446 | 0.094 | 0.094 | 0.094 | 0.094 |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| churches | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | lighting | 20 | 11 | 44 | 220 | 220 | 220 | 220 | 220 | | | | | | | | | | | 220 | 220 | 44 | 44 | 44 | 44 | 44 | 44 |
| 2 | megaphone | 8 | 30 | | 120 | 120 | 120 | 120 | 240 | 240 | 120 | 120 | 120 | 120 | | | | | | 120 | 120 | | | | | | |
| 3 | miscellaneous | 1 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| | sub total | | | 0.084 | 0.38 | 0.38 | 0.38 | 0.38 | 0.5 | 0.28 | 0.16 | 0.16 | 0.16 | 0.16 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.38 | 0.38 | 0.084 | 0.084 | 0.084 | 0.084 | 0.084 | 0.084 |
| mosque | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | lighting | 10 | 11 | 22 | 22 | 22 | 110 | 110 | 22 | | | | | | | | | | | | 110 | 110 | 110 | 22 | 22 | 22 | 22 |
| 2 | megaphone | 4 | 30 | | | | 120 | 120 | | | | | | | 120 | | | 120 | | | 120 | | 120 | | | | |
| 3 | miscellaneous | | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| | sub total | | | 0.062 | 0.062 | 0.062 | 0.27 | 0.27 | 0.062 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.16 | 0.04 | 0.04 | 0.16 | 0.04 | 0.04 | 0.27 | 0.15 | 0.27 | 0.062 | 0.062 | 0.062 | 0.062 |
| health center | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | lighting | 6 | 11 | 66 | 66 | 66 | 66 | 66 | 66 | | | | | | | | | | | | 66 | 66 | 66 | 66 | 66 | 66 | 66 |
| 2 | microscope | 1 | 20 | | | | | | | | 20 | 20 | 20 | 20 | | 20 | 20 | 20 | 20 | | | | | | | | |
| 3 | refrigrator | 1 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 |
| 4 | water heater | 1 | 1500 | | | | | | | | 1500 | | | 1500 | | 1500 | | | 1500 | | | | | | | | |
| 5 | miscellaneous | 1 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| | | | | 316 | 316 | 316 | 316 | 316 | 316 | 250 | 1770 | 270 | 270 | 1770 | 250 | 1770 | 270 | 270 | 1770 | 250 | 316 | 316 | 316 | 316 | 316 | 316 | 316 |
| | sub total | | | 0.316 | 0.316 | 0.316 | 0.316 | 0.316 | 0.316 | 0.25 | 1.77 | 0.27 | 0.27 | 1.77 | 0.25 | 1.77 | 0.27 | 0.27 | 1.77 | 0.25 | 0.316 | 0.316 | 0.316 | 0.316 | 0.316 | 0.316 | 0.316 |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Agricultural&flour mill | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | flour mill (7500) | | | | | | | | | | | 7500 | 7500 | 7500 | 7500 | | | 7500 | 7500 | 7500 | 7500 | | | | | | |
| 2 | pump (7x2000) | | | | | | | | | 14000 | 14000 | 14000 | 14000 | | | | 14000 | 14000 | 14000 | 14000 | | | | | | | |
| | sub total | | | | | | | | | 14 | 14 | 21.5 | 21.5 | 7.5 | 7.5 | 0 | 14 | 21.5 | 21.5 | 21.5 | 7.5 | | | | | | |
| | Total load(kw) | | | 20.356 | 20.65 | 20.65 | 20.86 | 20.86 | 50.78 | 71.03 | 72.426 | 78.626 | 72.026 | 59.526 | 58.006 | 104.7 | 64.41 | 72.026 | 73.41 | 72.026 | 65.318 | 95.376 | 95.496 | 94.936 | 94.936 | 94.936 | 26.956 |

Weekend hourly load estimation of the village

Load Estimation of large house

| S.No | Appliance Type | Quantity | Power(W) | period of time(hr) | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 00--1 | 1--2 | 2--3 | 3--4 | 4--5 | 5--6 | 6--7 | 7--8 | 8--9 | 9--10 | 10--11 | 11--12 | 12--13 | 13--14 | 14--15 | 15--16 | 16--17 | 17--18 | 18--19 | 19--20 | 20--21 | 21--22 | 22--23 | 23--00 |
| | Domostic | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | Lighting | 3 | 11 | | | | | | | | | | | | | | | | | | | 33 | 33 | 33 | 33 | 33 | |
| 2 | Radio | 1 | 10 | | | | | | | 10 | 10 | 10 | | | | 10 | | | | | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 3 | TV | 1 | 70 | | | | | | | | | | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | |
| 4 | Cooking | 1 | 3000 | | | | | | 166.7 | 166.7 | 166.7 | 166.7 | 167 | 166.7 | 166.7 | 166.7 | 166.7 | 166.7 | 166.7 | 166.7 | 166.7 | | | | | | |
| 5 | Miscellaneous | | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| | no.l.house | 180 | | | | | | | | | | | | | | | | | | | | | | | | | |
| | total | | | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 35.41 | 37.21 | 37.21 | 37.21 | 48 | 48.01 | 48.01 | 49.81 | 48.006 | 48.006 | 48.01 | 48.006 | 49.806 | 25.74 | 25.74 | 25.74 | 25.74 | 25.74 | 7.2 |

Load Estimation of small houses

| S.No | Appliance Type | Quantity | Power(W) | period of time(hr) | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 00--1 | 1--2 | 2--3 | 3--4 | 4--5 | 5--6 | 6--7 | 7--8 | 8--9 | 9--10 | 10--11 | 11--12 | 12--13 | 13--14 | 14--15 | 15--16 | 16--17 | 17--18 | 18--19 | 19--20 | 20--21 | 21--22 | 22--23 | 23--00 |
| | Domostic | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | Lighting | 3 | 11 | | | | | | | | | | | | | | | | | | | 33 | 33 | 33 | 33 | 33 | |
| 2 | Radio | 1 | 8 | | | | | | | 10 | 10 | 10 | | | | 10 | | | | | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 3 | TV | 1 | 70 | | | | | | | | | | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | |
| 4 | Miscellaneous | | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| | no.l.house | 480 | | | | | | | | | | | | | | | | | | | | | | | | | |
| | sub total | | | 14.4 | 14.4 | 14.4 | 14.4 | 14.4 | 14.4 | 19.2 | 19.2 | 19.2 | 48 | 48 | 48 | 52.8 | 48 | 48 | 48 | 48 | 52.8 | 68.64 | 68.64 | 68.64 | 68.64 | 68.64 | 19.2 |

Public load

| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| school | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | lighting | 36 | 11 | 44 | 44 | 44 | 44 | 44 | 44 | | | | | | | | | | | | 44 | 44 | 44 | 44 | 44 | 44 | 44 |
| 2 | office load | 1 | 0 | | | | | | | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | | | | | |
| 3 | miscellaneous | 1 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| | sub total | | 0.061 | 0.094 | 0.094 | 0.094 | 0.094 | 0.094 | 0.094 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.094 | 0.094 | 0.094 | 0.094 | 0.094 | 0.094 | 0.094 |
| churches | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | lighting | 20 | 11 | 44 | 220 | 220 | 220 | 220 | 220 | | | | | | | | | | | 220 | 220 | 44 | 44 | 44 | 44 | 44 | 44 |
| 2 | megaphone | 8 | 30 | | 120 | 120 | 120 | 120 | 240 | 240 | 120 | 120 | 120 | 120 | | | | | | 120 | 120 | | | | | | |
| 3 | miscellaneous | 1 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| | sub total | | | 0.084 | 0.38 | 0.38 | 0.38 | 0.38 | 0.5 | 0.28 | 0.16 | 0.16 | 0.16 | 0.16 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.38 | 0.38 | 0.084 | 0.084 | 0.084 | 0.084 | 0.084 | 0.084 |
| mosque | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | lighting | 10 | 11 | 22 | 22 | 22 | 110 | 110 | 22 | | | | | | | | | | | | 110 | 110 | 110 | 22 | 22 | 22 | 22 |
| 2 | megaphone | 4 | 30 | | | | 120 | 120 | | | | | | | 120 | | | 120 | | | 120 | | 120 | | | | |
| 3 | miscellaneous | | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| | sub total | | | 0.062 | 0.062 | 0.062 | 0.27 | 0.27 | 0.062 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.16 | 0.04 | 0.04 | 0.16 | 0.04 | 0.04 | 0.27 | 0.15 | 0.27 | 0.062 | 0.062 | 0.062 | 0.062 |
| health center | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | lighting | 6 | 11 | 66 | 66 | 66 | 66 | 66 | 66 | | | | | | | | | | | | 66 | 66 | 66 | 66 | 66 | 66 | 66 |
| 2 | microscope | 1 | 20 | | | | | | | | 20 | 20 | 20 | 20 | | 20 | 20 | 20 | 20 | | | | | | | | |
| 3 | refrigrator | 1 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 |
| 4 | water heater | 1 | 1500 | | | | | | | | 1500 | | | 0 | | 0 | | | 0 | | | | | | | | |
| 5 | miscellaneous | 1 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| | | | | 316 | 316 | 316 | 316 | 316 | 316 | 250 | 1770 | 270 | 270 | 270 | 250 | 270 | 270 | 270 | 270 | 250 | 316 | 316 | 316 | 316 | 316 | 316 | 316 |
| | sub total | | | 0.316 | 0.316 | 0.316 | 0.316 | 0.316 | 0.316 | 0.25 | 1.77 | 0.27 | 0.27 | 0.27 | 0.25 | 0.27 | 0.27 | 0.27 | 0.27 | 0.25 | 0.316 | 0.316 | 0.316 | 0.316 | 0.316 | 0.316 | 0.316 |
| Agricultural&flour mill | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | flour mill (7500) | | | | | | | | | | | 0 | 0 | 0 | 0 | | | 0 | 0 | 0 | 0 | | | | | | |
| 2 | pump (7x2000) | | | | | | | | | 0 | 0 | 0 | 0 | | | | 0 | 0 | 0 | 0 | | | | | | | |
| | sub total | | | | | | | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| | Total load(kw) | | | 20.356 | 20.652 | 20.652 | 20.86 | 20.86 | 50.78 | 57.03 | 58.43 | 56.93 | 96.5 | 96.53 | 96.51 | 103 | 96.406 | 96.526 | 96.41 | 96.726 | 103.666 | 95.024 | 95.144 | 94.936 | 94.936 | 94.936 | 26.956 |

Summer hourly load estimation of the village

Load Estimation of large house

| S.No | Appliance Type | Quantity | Power(W) | period of time(hr) | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 00--1 | 1--2 | 2--3 | 3--4 | 4--5 | 5--6 | 6--7 | 7--8 | 8--9 | 9--10 | 10--11 | 11--12 | 12--13 | 13--14 | 14--15 | 15--16 | 16--17 | 17--18 | 18--19 | 19--20 | 20--21 | 21--22 | 22--23 | 23--00 |
| | Domostic | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | Lighting | 3 | 11 | | | | | | | | | | | | | | | | | | | 33 | 33 | 33 | 33 | 33 | |
| 1 | Radio | 1 | 10 | | | | | | | 10 | 10 | 10 | | | | 10 | | | | | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 2 | TV | 1 | 70 | | | | | | | | | | | | | 70 | | | | | | 70 | 70 | 70 | 70 | 70 | |
| 3 | Cooking | 1 | 3000 | | | | | | 166.7 | 167 | 167 | 166.7 | 166.7 | 166.7 | 166.7 | 166.7 | 166.7 | 166.7 | 166.7 | 166.7 | 166.7 | | | | | | |
| 4 | Miscellaneous | | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| | no.l.house | 180 | | | | | | | | | | | | | | | | | | | | | | | | | |
| | sub total | | | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 35.41 | 37.2 | 37.2 | 37.21 | 35.41 | 35.41 | 35.406 | 49.806 | 35.406 | 35.406 | 35.406 | 35.406 | 37.206 | 25.74 | 25.74 | 25.74 | 25.74 | 25.74 | 7.2 |

Load Estimation of small houses

| S.No | Appliance Type | Quantity | Power(W) | period of time(hr) | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 00--1 | 1--2 | 2--3 | 3--4 | 4--5 | 5--6 | 6--7 | 7--8 | 8--9 | 9--10 | 10--11 | 11--12 | 12--13 | 13--14 | 14--15 | 15--16 | 16--17 | 17--18 | 18--19 | 19--20 | 20--21 | 21--22 | 22--23 | 23--00 |
| | Domostic | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | Lighting | 3 | 11 | | | | | | | | | | | | | | | | | | | 33 | 33 | 33 | 33 | 33 | |
| 2 | Radio | 1 | 8 | | | | | | | 10 | 10 | 10 | | | | 10 | | | | | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 3 | TV | 1 | 70 | | | | | | | | | | | | | 70 | | | | | | 70 | 70 | 70 | 70 | 70 | |
| 4 | Miscellaneous | | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| | no.l.house | 480 | | | | | | | | | | | | | | | | | | | | | | | | | |
| | sub total | | | 14.4 | 14.4 | 14.4 | 14.4 | 14.4 | 14.4 | 19.2 | 19.2 | 19.2 | 14.4 | 14.4 | 14.4 | 52.8 | 14.4 | 14.4 | 14.4 | 14.4 | 19.2 | 68.64 | 68.64 | 68.64 | 68.64 | 68.64 | 19.2 |

Public load

school

| S.No | Appliance Type | Quantity | Power(W) | 00--1 | 1--2 | 2--3 | 3--4 | 4--5 | 5--6 | 6--7 | 7--8 | 8--9 | 9--10 | 10--11 | 11--12 | 12--13 | 13--14 | 14--15 | 15--16 | 16--17 | 17--18 | 18--19 | 19--20 | 20--21 | 21--22 | 22--23 | 23--00 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | lighting | 36 | 11 | 44 | 44 | 44 | 44 | 44 | 44 | | | | | | | | | | | | 44 | 44 | 44 | 44 | 44 | 44 | 44 |
| 2 | office load | 1 | 200 | | | | | | | | | | | | | | | | | | | | | | | | |
| 3 | miscellaneous | 1 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| | sub total | | 0.261 | 0.094 | 0.09 | 0.094 | 0.094 | 0.09 | 0.094 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.094 | 0.094 | 0.094 | 0.094 | 0.094 | 0.094 | 0.094 |
| churches | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | lighting | 20 | 11 | 44 | 220 | 220 | 220 | 220 | 220 | | | | | | | | | | | 220 | 220 | 44 | 44 | 44 | 44 | 44 | 44 |
| 2 | megaphone | 8 | 30 | | 120 | 120 | 120 | 120 | 240 | 240 | 120 | 120 | 120 | 120 | | | | | | 120 | 120 | | | | | | |
| 3 | miscellaneous | 1 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| | sub total | | | 0.084 | 0.38 | 0.38 | 0.38 | 0.38 | 0.5 | 0.28 | 0.16 | 0.16 | 0.16 | 0.16 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.38 | 0.38 | 0.084 | 0.084 | 0.084 | 0.084 | 0.084 | 0.084 |
| mosque | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | lighting | 10 | 11 | 22 | 22 | 22 | 110 | 110 | 22 | | | | | | | | | | | | 110 | 110 | 110 | 22 | 22 | 22 | 22 |
| 2 | megaphone | 4 | 30 | | | | 120 | 120 | | | | | | | 120 | | | 120 | | | 120 | | 120 | | | | |
| 3 | miscellaneous | | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| | sub total | | | 0.062 | 0.06 | 0.062 | 0.27 | 0.27 | 0.062 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.16 | 0.04 | 0.04 | 0.16 | 0.04 | 0.04 | 0.27 | 0.15 | 0.27 | 0.062 | 0.062 | 0.062 | 0.062 |
| health center | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | lighting | 6 | 11 | 66 | 66 | 66 | 66 | 66 | 66 | | | | | | | | | | | | 66 | 66 | 66 | 66 | 66 | 66 | 66 |
| 2 | microscope | 1 | 20 | | | | | | | | 20 | 20 | 20 | 20 | | 20 | 20 | 20 | 20 | | | | | | | | |
| 3 | refrigrator | 1 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 |
| 4 | water heater | 1 | 1500 | | | | | | | | 1500 | | | 1500 | | 1500 | | | 1500 | | | | | | | | |
| 5 | miscellaneous | 1 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| | | | | 316 | 316 | 316 | 316 | 316 | 316 | 250 | 1770 | 270 | 270 | 1770 | 250 | 1770 | 270 | 270 | 1770 | 250 | 316 | 316 | 316 | 316 | 316 | 316 | 316 |
| | sub total | | | 0.316 | 0.32 | 0.316 | 0.316 | 0.32 | 0.316 | 0.25 | 1.77 | 0.27 | 0.27 | 1.77 | 0.25 | 1.77 | 0.27 | 0.27 | 1.77 | 0.25 | 0.316 | 0.316 | 0.316 | 0.316 | 0.316 | 0.316 | 0.316 |
| | Agricultural&flour mill | | | | | | | | | | | | | | | | | | | | | | | | | | |
| flour mill (7500) | | | | | | | | | | | | 7500 | 7500 | 7500 | 7500 | | | 7500 | 7500 | 7500 | 7500 | | | | | | |
| pump (7x2000) | | | | | | | | | | 0 | 0 | 0 | 0 | | | | 0 | 0 | 0 | 0 | | | | | | | |
| | sub total | | | | | | | | | 0 | 0 | 7.5 | 7.5 | 7.5 | 7.5 | 0 | 0 | 7.5 | 7.5 | 7.5 | 7.5 | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | Total load(kw) | | | 20.36 | 20.7 | 20.65 | 20.86 | 20.9 | 50.78 | 57 | 58.4 | 64.43 | 57.83 | 59.33 | 57.806 | 104.51 | 50.206 | 57.826 | 59.206 | 58.026 | 64.966 | 95.02 | 95.144 | 94.94 | 94.936 | 94.936 | 26.956 |

# Appendix B

Technical Data of EOLTEC CHINOOK 17-65 Wind Turbine

| | |
|---|---|
| Rated power | 65 kW |
| Cut-in wind speed | 2.3 m/s |
| Rated wind speed | 10 m/s |
| Cut-out wind speed | 20 m/s |
| Rated wind speed | 11 m/s |
| Survival speed | 50 m/s |
| Number of rotor blades | 3 |
| Rotor diameter | 17 m |
| Swept area | 227 $m^2$ |
| Rotor speed (variable) | 25-75 rpm |
| Power control | Active blade pitch control |
| Hub height | 32-40 m |

Power Curve of the selected wind turbine